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FORMATION OF PARTIALLY AND FULLY ELABORATED GENERALIZED EQUIVALENCE CLASSES

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Most complex categories observed in real-world settings consist of perceptually disparate stimuli, such as a picture of a person's face, the person's name as written, and the same name as heard, as well as dimensional variants of some or all of these stimuli. The stimuli function as members of a single partially or fully elaborated generalized equivalence class when they occasion the mutual selection of each other after the establishment of some subset of relations among the stimuli. Indeed, it is these generalized relations among stimuli that enable an individual to respond appropriately to the inevitable flux of natural environments. The present experiments involved procedures for producing both types of generalized equivalence class and for evaluating their retention. Granting the formal and functional similarities that exist between generalized equivalence classes and natural categories, natural kinds, and fuzzy superordinate classes, the variables responsible for the emergence of the former might also account for the emergence of the latter three phenomena. In Experiment 1, After forming an A′–B′ class, a B′–C relation was trained and generalization tests were conducted with B′–C, C–B′, A′–C, and C′–A. Two of 5 participants passed the tests documenting the formation of A′–B′–C classes. Failures occurred in the A′–C and C–A′ tests but not the B′–C and C–B′ tests. Failures were also correlated with time between A′–B′ class formation and C-based testing and with the absence of baseline confirmation when training and testing were separated by about one week. Experiment 2 replicated Experiment 1 but presented baseline confirmation probes immediatley prior to testing when training and testing were separated by one week; all participants then formed partially elaborated generalized equivalence classes. In Experiment 3, 5 of 6 participants formed fully elaborated generalized equivalence classes, represented as A′=B′=C′ .

Key words: partially elaborated generalized equivalence class, fully elaborated generalized equivalence class, linked perceptual class, computer keyboard as response device, conditional discrimination, college students

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Most, if not all, of the complex stimulus categories found in natural settings consist of stimuli that are perceived as physically disparate and other stimuli that are perceptually similar to each other. Examples are the face of an individual seen from different vantage points, the sounds of the individual's voice when heard from various distances, and an individual's name written in different scripts by different hands. Stimuli are said to function as an equivalence class when one of them leads to the selection of the others (Critchfield & Fienup, 2008). This occurs when a minimal number of conditional discriminations have been established between single stimuli in each of the disparate domains (i.e., the faces, voices, and written names in the previous example). Once a class has been induced, a response to, or a function acquired by, one of the stimuli in the class should generalize to the other class members without direct training. In fact, this is a critical test of whether the class exists. As such, the control of an individual's behavior by such a class should enable him or her to respond appropriately to the inevitably varied stimuli encountered in natural settings without the occurrence of direct training. Control of behavior by complex classes such as these is of singular adaptive value for an individual in an ever-changing environment.

These classes have been called natural categories, natural kinds, or fuzzy superordinate categories (Fields & Reeve, 2000, 2001; Lane, Clow, Innis, & Critchfield, 1998; Rehfeldt & Hayes, 2000; Rosch & Mervis, 1975; Wittgenstein, 1953). When established in a laboratory, they have been referred to as generalized equivalence classes (Branch,

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1994; Fields, Reeve, Adams, & Verhave, 1991) and vary in their complexity. To date, research has explored the formation of two simplified forms of generalized equivalence classes. The present experiments addressed the formation of the more complex forms of generalized equivalence classes that more closely approximate the categories found in natural settings. In fact, the identification of the variables responsible for the establishment of generalized equivalence classes might possibly account for the emergence of the complex categories in natural settings.

A perceptual class contains a potentially infinite number of exemplars that bear some resemblance to each other, can be arrayed along a continuum, and produce the mutual selection of each other (Fields & Reeve, 2001; Keller & Schoenfeld, 1950; Wasserman, Keidinger, & Bhatt, 1988; Wright, Cook, Rivera, Sands, & Delius, 1988). An equivalence class is a finite set of stimuli that do not bear any resemblance to each other, i.e., cannot be placed along a single continnuum. After establishing a total of N-1 relations among the N stimuli in an equivalence class, all will produce mutual selection of each other (Fields & Verhave, 1987; Sidman, 1971, 1994). In laboratory settings, a generalized equivalence class can be constructed by merging an equivalence class and at least one perceptual class, or by merging two distinct perceptual classes (Fields & Reeve, 2000, 2001). In either case, the merger of the classes can be accomplished by training at least one relation between one stimulus in each of two classes. Generalized equivalence classes come in four varieties: (a) minimally elaborated generalized equivalence classes, (b) linked perceptual classes, (c) partially elaborated generalized equivalence classes, and (d) fully elaborated generalized equivalence classes (Fields & Reeve, 2001).

A *minimally elaborated generalized equivalence class* consists of an equivalence class in which one of the stimuli in the equivalence class is also a member of a perceptual class. A number of studies have demonstrated the formation of minimally elaborated generalized equivalence classes (Fields, Adams, Brown, & Verhave, 1993a; Fields, Adams, Buffington, Yang, & Verhave, 1996; Fields, Matneja, Varelas, & Belanich, 2003; Fields, Reeve, Adams, Brown, & Verhave, 1997a; Galizio, Stewart, & Pilgrim, 2004; Lane et al., 1998; Rehfeldt & Hayes, 2000), their retention (Rehfeldt, & Hayes, 2000), and the ability of these classes to act as function transfer networks (Barnes & Keenan, 1993; Belanich & Fields, 2003; Fields et al., 1996).

A *linked perceptual class* consists of two distinct perceptual classes. The members of one class differentially produce the mutual selection of the members of the other class after the formation of at least one conditional discrimination that links the two perceptual classes. A medical example would be the tactile stimuli produced by a subdural tumor upon palpation (one perceptual class) and visual images of the tumor as they appear in a CT scan (the other perceptual class). The likelihood of forming a linked perceptual class is influenced by a variety of testing variables (Fields et al., 2005) and training variables (Fields et al., 2007). Linked perceptual classes also act as function transfer networks (Fields & Garruto, unpublished manuscript).

A *partially elaborated generalized equivalence class* consists of an equivalence class in which more than one but less than the N stimuli in the class are also members of perceptual classes, and the members of all classes occasion the mutual selection of each other. In an example from biometric identification, a partially elaborated generalized equivalence class could be formed from a *single* corneal image along with several facial images of the person (one perceptual class) and sounds of the person's voice (another perceptual class). Thus, the merger of the single corneal image and the members of the linked perceptual classes would form a partially elaborated generalized equivalence class.

A *fully elaborated generalized equivalence class* consists of an equivalence class where each member of that class is also a member of a perceptual class. All of these stimuli would function as members of a fully elaborated generalized equivalence class if the members of each perceptual class occasioned the selection of the stimuli in the other classes. An example includes the sounds made by a predator species (one perceptual class), the visual appearance of members of the species (a second perceptual class), and their scents (a third perceptual class).

We are not aware of any previous studies that explored the formation of partially elaborated or fully elaborated generalized equivalence classes. Experiments 1 and 2 explored the formation of the former. Experiment 3 explored the formation of the latter.

EXPERIMENT 1

Experiment 1 attempted to establish partially elaborated generalized equivalence classes. First, multiple-exemplar training was used to induce novel perceptual classes represented symbolically as A1′, A2′, B1′, and B2′. Linked perceptual classes, represented symbolically as A1′=B1′ and A2′=B2′, were established by training conditional discriminations between the A′ and B′ classes. Then a member of each B′ class was linked by training to one new stimulus represented as C1 and C2, respectively. The expansion of linked perceptual classes to partially elaborated generalized equivalence classes was evaluated by the presentation of probes that measured the emergence of new relations among the two C stimuli and the stimuli in the corresponding A′ and B′ classes. Class-consistent responding documented the emergence of the partially elaborated generalized equivalence class: A1′=B1′=C1 and A2′=B2′=C2.

METHOD

Participants

Six undergraduate students enrolled in a psychology course at Queens College served as the participants and were given partial course credit upon completion of the experiment. Three participants were randomly assigned to each of Groups 1 and 2. All participants read and acknowledged the Informed Consent Statement given to them before the start of the experiment. One participant was subsequently dropped from Group 1. The experiment lasted from 4 to 5 hr and was conducted in two or three sessions, each of which was approximately 2 hr long. (See ''Stages and Phases'' in the Procedure section for a description of the two groups.)

Apparatus

Hardware and software. The experiment was conducted with an IBM-compatible computer that displayed all stimuli on a 15-in color monitor. Responses consisted of touching specific keys on a standard QWERTY keyboard. The experiment was controlled by custom software that programmed all stimulus presentations and recorded all keyboard responses.

Stimuli. All stimuli were presented in 5 × 5-cm colored squares (without contrasting borders) against a black background on the computer monitor. Sets of semantically related English words were used initially. Later, morphed images of pictorial stimuli in four domains, W, X, Y, and Z were used to induce generalized categorization repertoires in the preliminary phase of Experiments 1, 2, and 3. The main phase of Experiments 1 and 2 used stimuli that were morphed images in two different domains, A and B. In contrast, the main phase of Experiment 3 used stimuli that were morphed images in three different domains, A, B, and C.

The stimuli used to induce a generalized categorization repertoire in Experiments 1, 2, and 3 are illustrated in Figure 1. They are pictorial images drawn from Domains W, X, Y, and Z, which were referred to as Female–Male, Abstract Pictures, Truck–Car, and North Korea–Germany, respectively. The stimuli in the North Korea–Germany domain were banded elevation satellite images (SAT), 100 km × 100 km, from those countries. The stimuli were presented as multicolored RGB 24-bit images.

The stimuli shown in Figure 2 were used in the main phases of each experiment. These stimuli were selected from Domains A, B, and C, and were named Tree–Cat, Haiti–California, and Bosnia–Cuba, respectively. The stimuli in Haiti–California, and Bosnia–Cuba domains were satellite images, 100 km × 100 km of landmasses in the designated regions. The Haiti–California images were banded elevation satellite images, but the stimuli in the Bosnia–Cuba domain were false-color satellite images. The stimuli in Domains A and B were used in Experiments 1, 2, and 3, but those in Domain C were used in Experiment 3 only.

The stimuli that were the endpoints of each domain are depicted in rows _1a and _2a in Figures 1 and 2. Stimuli that varied systematically between the endpoints of each domain were created with a commercially available morphing software program (Figuracion, 1998). These intermediate stimuli in a domain were called variants and were produced by superimposing the endpoint stimuli and changing their relative saliencies. Each variant

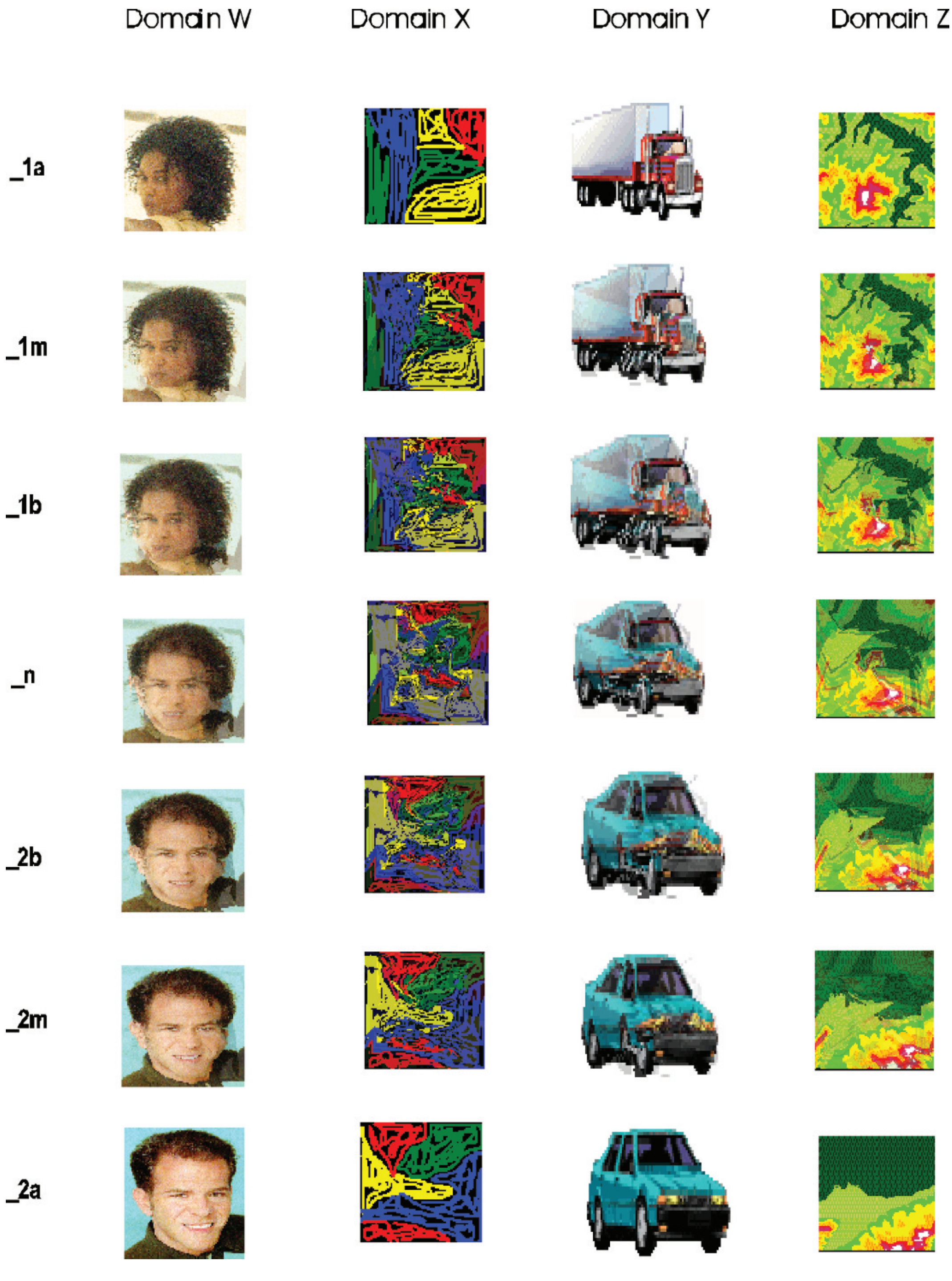

Fig. 1. Anchor, midpoint, and boundary stimuli for the perceptual classes at each end of the W, X, Y, and Z domains along with the neither stimulus in the respective domains. See text for details.

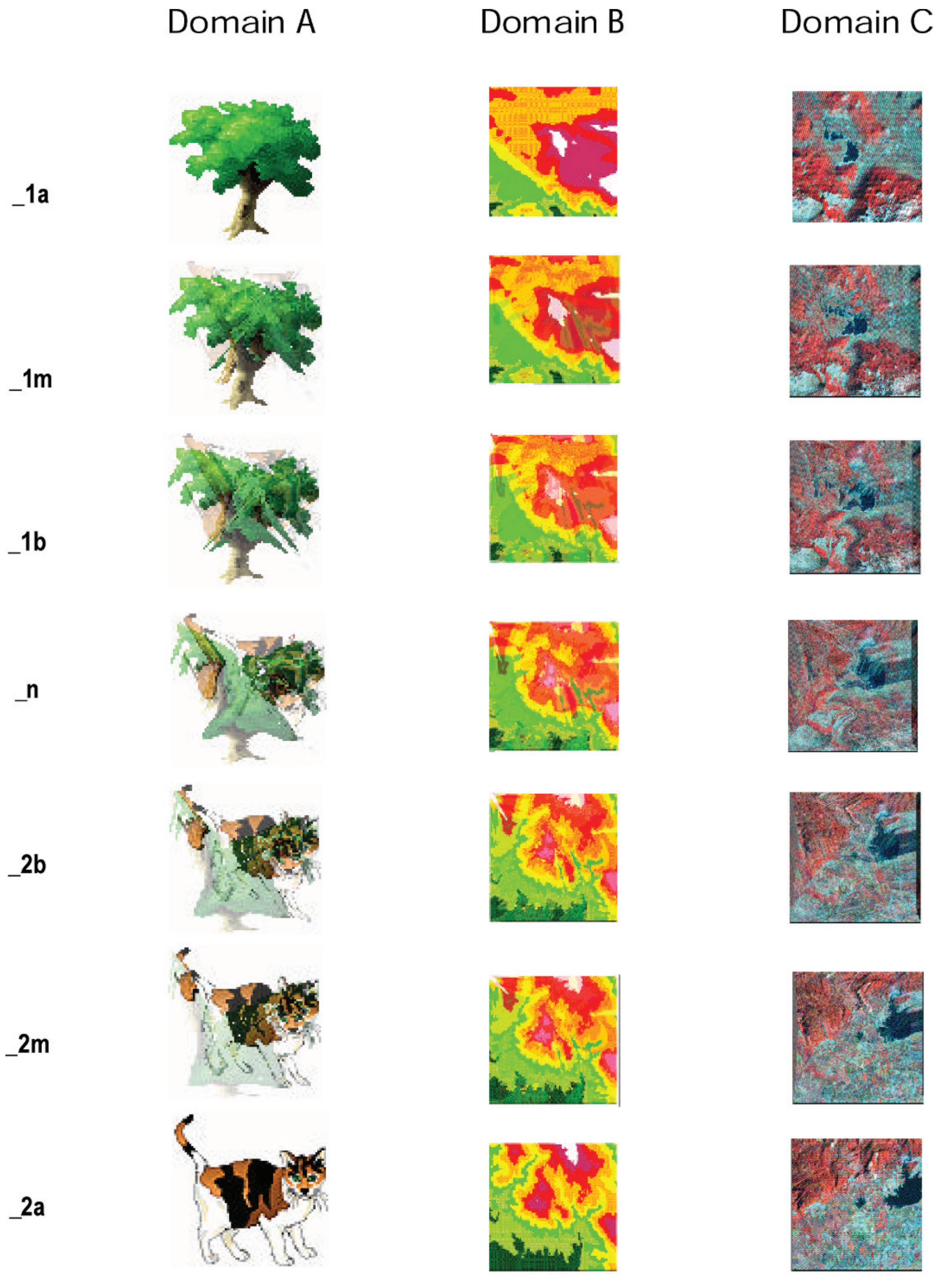

Fig. 2. The stimuli in Domains A, B, and C. See text for details.

was assigned a unit value that indicated its relative position along a continuous program-generated dimension. For stimuli in Domains A and C, the software assigned unit values 00 and 50 to the endpoint stimuli and generated 48 variants between these endpoints. The 15 variants used in the experiment had unit values of 03, 06, 09, 12, 15, 18, 21, 25, 28, 31, 34, 37, 40, 43, and 47. For stimuli in Domains W, X, Y, Z, and B, the software assigned values 000 and 500 to the endpoint stimuli and generated 498 variants between these endpoints. The 14 variants used in the experiments had values of 030, 070, 100, 130, 170, 210, 250, 280, 310, 340, 370, 390, 430, and 470. The stimuli in the B, C and Z domains are different satellite images. Therefore, the endpoints and variants in a satellite domain were denoted with SAT preceding the value of the variants, e.g., SAT-370.

The variants next to the endpoints of the domains, that is, those with the lowest and highest values, were designated as members of Class 1 and 2, respectively. For each class, the endpoint, which was the most clearly perceived member of the perceptual class, was referred to as its anchor (a) stimulus. The anchor stimuli in Classes 1 and 2 in Domain W were designated W1a and W2a. The anchor stimuli in Classes 1 and 2 for each domain are illustrated in the top and bottom rows, respectively, of Figure 1. The variant most distant from the anchor stimulus of a class that was judged (see below for details of the perceptual judgment procedure) to be related to the anchor of that class was referred to as its boundary (b) stimulus. The boundary stimuli in Classes 1 and 2 in Domain W were designated as W1b and W2b, respectively. The boundary stimuli for Classes 1 and 2 for each domain are illustrated in rows _1b and _2b in Figure 1.

As already noted, the anchor stimulus was the most clearly perceived member in its perceptual class, and the boundary stimulus was the most ambiguous member in the same class. The variant judged to be perceptually equidistant between the anchor and boundary stimuli in a class was referred to as its midpoint (m) stimulus. The midpoint stimuli in Classes 1 and 2 in Domain W were designated as W1m and W2m, respectively. The midpoint stimuli for Classes 1 and 2 for each domain are illustrated in rows _1m and _2m in Figure 1. The variants between the boundaries of the two classes in a domain were not considered to be members of either class. The variant judged to be perceptually equidistant between the boundary stimuli of the two classes in a domain was called the neither (n) stimulus for the domain (Adams, Fields, & Verhave, 1993; Fields et al., 1993a). For Domain W, the neither stimulus was designated as Wn and appears for each domain in row _n in Figure 1.

The values assigned to the variants used as the midpoint, the boundary, and the neither stimuli in Domains W through Z were defined by a group of five independent observers using a bisection procedure. For a given domain, an observer was shown the anchor stimulus for Class 1, and then was asked to sort through the remaining variants and select the variant that was most distant from the anchor but was still related to it. The value of that specific variant was then designated as the boundary stimulus for Class 1. Each observer was then shown the anchor and boundary stimuli of Class 1 and asked to sort through the variants between them and select the variant that was perceptually equidistant from each. The value of the selected variant became the midpoint stimulus of Class 1. After doing the same for Class 2, the observer was presented with boundary stimuli from Classes 1 and 2 and asked to sort through the variants between the boundaries and select the variant that was equidistant from each. The value of that selected variant became the neither stimulus for that domain. The values selected by the observers were averaged for each midpoint stimulus, each boundary stimulus, and each neither stimulus for each class and domain. The stimuli associated with the resultant means are illustrated in rows _1m through _2m for Domains W, X, Y, and Z.

Figure 2 depicts stimuli representative of the anchor, midpoint, and boundary stimuli from Classes A1′, B1′, and C1′ (see the first, second and third rows of the figure) and the anchor, midpoint, and boundary stimuli from Classes A2′, B2′, and C2′ (see the fifth, sixth, and seventh rows of the figure), as well as the neither stimulus from each domain in the fourth row of the figure. The variants that appear in the figure are representative of the midpoints and boundaries because the actual values assigned to these stimuli were based on performances measured in Phase 3 of Experiments 1, 2, and 3 and, thus, could vary with each participant.

Procedure

Trial format and contingencies. All trials in the experiment were presented in a matching-to-sample format (Cumming & Berryman, 1965). Each trial involved the presentation of a sample and two or three comparison stimuli. The sample stimulus was a variant drawn from one of two sets like those described in Figure 2. One comparison stimulus was drawn from the same set as the sample stimulus on that trial and was called the positive comparison. Another comparison stimulus was not from the same set as the sample stimulus and was called the negative comparison. A third comparison stimulus, denoted on the computer monitor with the phrase ''If Neither, Press 4,'' was referred to as the neither comparison. Its selection by the participant implied that neither the positive nor the negative comparison was related to the sample on that trial (Innis, Lane, Miller, & Critchfield, 1998). The identification of the stimuli used as positive and negative comparisons is described below.

The sample was presented on the upper portion of the monitor and was centered horizontally. The positive and negative comparisons were presented below the sample and to the left and right of the sample. The location of the positive comparison was randomly assigned with the stipulation that it would appear the same number of times on the left and on the right. The upper edges of the comparisons were below the lower edge of the sample. The right edge of the left comparison was to the left of the left edge of the sample, and the left edge of the right comparison was to the right of the right edge of the sample. The neither option, when included on a trial, was presented below the other comparisons and centered horizontally on the monitor.

Trial-block organization and feedback reduction. Each phase of the experiment consisted of blocks of trials. In all phases, the trials in a block were presented in a randomized order without replacement. A trial began when ''Press ENTER'' appeared on the screen. Pressing the ENTER key cleared the screen and displayed a sample. Pressing the space bar displayed two comparisons while the sample remained on the screen. During trials in which the third comparison was programmed, the words ''If NEITHER press 4'' appeared below and between the two comparisons. During a trial, the participant could select a comparison by pressing the ''1'' or ''2'' key. Pressing the ''4'' key was the response that selected the neither comparison when it was available. Selection of a comparison cleared the screen and immediately displayed a feedback message centered on the screen.

When *informative* feedback was presented, the words ''RIGHT'' or ''WRONG'' appeared, depending on the accuracy of the comparison selection. The message remained on the screen until the participant pressed the ''R'' key (R for RIGHT) in the presence of the word ''Right'' or the ''W'' key (W for WRONG) in the presence of the word ''Wrong.'' These key presses were observing responses for the informative feedback. During some training trials and all testing trials, *uninformative* feedback was presented after a comparison was selected. This consisted of dashed lines that bracketed the letter E (i.e., - - E - -) and signaled the end of a trial. This cue remained on the screen until the participant pressed the ''E'' key, which served as an observing response for the uninformative feedback. The occurrence of an appropriate R, W, or E response cleared the monitor and enabled the start of the next trial (Fields, Landon-Jimenez, Buffington, & Adams, 1995).

At the start of training, all the trials in a block resulted in informative feedback after each comparison selection, i.e., 100% feedback. The same block was presented repeatedly with 100% feedback until the trials within the block produced 100% correct responding. This was referred to as the mastery criterion. In subsequently presented blocks, the percentage of trials that produced informative feedback was systematically reduced to 75%, 25%, and finally to 0% per block as long as the mastery criterion was maintained in the block. During this feedback reduction procedure, the trials that produced informative feedback were randomly determined. Each block ended with the presentation of an on-screen message, ''Press ENTER to begin the next block.'' If 100% correct responding was not achieved within three blocks at a given feedback level during training, the participant was returned to the previous feedback level during the next block and remained there until the mastery criterion was achieved. In practice, this was a very infrequent occurrence.

Experimental phases. The experiment was conducted in seven phases. In Phase 1, participants were taught the responses needed to perform on the trials throughout the experiment. In Phase 2, a generalized categorization repertoire was established with multiple-exemplar training that used stimuli in a number of different stimulus domains. In Phase 3, primary generalization tests were conducted with stimuli in domains A and B to determine the widths of the two perceptual classes in each end of a domain and the variants in each class that served as midpoints and boundaries. In Phase 4, conditional discriminations were established between stimuli from one class in domain A and one class in domain B, after which probes were presented to assess the symmetrical properties of the stimuli in the A–B relation. In Phase 5, cross-class probes were presented to track the emergence of linked perceptual classes. In Phase 6, conditional discriminations were formed between the B anchor stimuli and the C stimuli, after which probes were presented to assess the symmetrical properties of the stimuli in the B–C relation. In Phase 7, participants were presented with probes to document the emergence of partially elaborated generalized equivalence classes.

Phase 1: Instructions and keyboard familiarization. Prior to the experiment, participants were presented with the following instructions on the screen of the monitor:

> Thank you for volunteering to participate in this experiment. PLEASE DO NOT TOUCH ANY OF THE KEYS ON THE KEYBOARD YET! In this experiment you will be presented with many trials. Each trial contains three or four CUES. These will be familiar and unfamiliar picture images. YOUR TASK IS TO DISCOVER HOW TO RESPOND CORRECTLY TO THE CUES. Initially, there will also be INSTRUCTIONS that tell you how to respond to the cues, and LABELS that will help you to identify the cues on the screen. The labels and the instructions that tell you which KEYS to press will slowly disappear. Your task will be to RESPOND CORRECTLY to the CUES and the INSTRUCTIONS by pressing certain keys on the computer's keyboard. The experiment is conducted in phases. When each phase ends, the screen will sometimes tell you how you did. If you want to take a break at any time, please call the experimenter. PRESS THE SPACEBAR TO CONTINUE.

After pressing the space bar, participants were trained to emit the appropriate keyboard responses to complete a trial. This phase involved the repeated presentation of a block of 16 trials. Trials contained three English words, such as KING, QUEEN, and CAMEL. The semantic relation between the sample word (e.g., KING) and one of the comparisons (e.g., QUEEN) was used to prompt the selection of the correct comparison. The words RIGHT or WRONG followed each comparison selection. Correct responding to the stimuli in a trial was facilitated by the presentation of instructional prompts (e.g., ''Make your choice by pressing 1 or 2'', ''Press R to continue'', ''Press W to continue'', or ''Press E to continue'') which were systematically deleted across trials as long as the participant made correct responses. Whenever a participant pressed a nonexperimentally defined key during a trial, the instruction that prompted the appropriate key press reappeared on the screen during that trial. (For further details, see Fields, Adams, Verhave, & Newman, 1990 and Fields et al., 1997b). Phase 1 ended when the sample and comparison stimuli were presented without prompts, and performance was at 100% accuracy during a single block. In the remaining phases, instructional prompts were temporarily reinstated whenever a participant pressed a nonexperimentally defined key during a trial.

Phase 2. Induction of a generalized categorization repertoire. In preparation for Phase 3, training began with stimuli in Domain W. The anchor, midpoint, and boundary stimuli from Classes 1 and 2 and the neither stimulus from the same domain were presented four times each as samples in randomized order across trials in the training block. Thus, each block consisted of 28 trials. On all trials, the comparisons consisted of the anchor stimuli from classes 1 and 2 and the neither stimulus. For example, informative feedback (''RIGHT'') was presented for the selection of W1a when W1a, W1m, or W1b was the sample, for the selection of W2a when W2a, W2m, or W2b was the sample stimulus, and for the selection of the neither stimulus when Wn was the sample. Otherwise, ''WRONG'' was presented. The same block was repeated until a correct response occurred on all trials. The same procedure was then repeated with the stimuli in Domains X, Y, and Z. The final performances in each domain demonstrated that the three stimuli in each class of the domain produced the selection of the anchor stimulus from the same end of the domain, and the neither stimulus in the domain produced the selection of the neither comparison. In other words, the training procedure resulted in the formation of two functionally independent perceptual classes (Reeve & Fields, 2001) in each of the four domains.

Phase 3: Emergence of perceptual classes in Domains A and B. Phase 3 documented the emergence of two perceptual classes in Domain A (A1′ and A2′) and two perceptual classes in Domain B (B1′ and B2′) for each participant. These four perceptual classes were used in the subsequent phases to create two linked perceptual classes and two partially elaborated generalized equivalence classes.

The width of each perceptual class was equal to the range of values that separated the anchor and boundary stimuli in that class. As the value of the anchor stimulus in each class was arbitrarily set to zero, the width of each class was indexed by the value of the boundary stimulus for that class. Previous research had shown that the value of the boundary stimulus in a perceptual class can vary as a function of whether it is used as a sample or as a comparison (Fields et al., 2002a; Fields et al., 2002b; Fields et al., 2005). In Phase 3, the values of the boundary stimuli when used as samples were determined using *variant-to-base* generalization tests, and the values of the boundary stimuli when used as comparisons were determined using *base-to-variant* generalization tests.

Variant-to-base generalization tests. During the variant-to-base test format, the anchor stimuli and all of the variants in a domain (e.g., SAT-000 through SAT-500 for Domain B) were presented as samples on different trials. In addition, the anchor stimuli from the domain (e.g., SAT-000 and SAT-500) and the neither comparison were presented as the comparisons on all trials. No informative feedback was provided. The on-screen location of the anchor stimulus comparisons was randomized without replacement throughout a block. Each variant was presented twice within a block and in randomized order without replacement.

Base-to-variant generalization tests. During the base-to-variant test format, a trial began with the presentation of a sample which was one of the two anchor stimuli from a domain (i.e., SAT-000 or SAT-500). For each sample, the other anchor stimulus and the neither comparison were presented as two of the three comparisons on all trials. The third comparison on each trial was one of the variants. No informative feedback was provided. The variants were presented on a random basis across trials. The order in which the two samples were presented was also randomized. The on-screen location of the comparisons was randomized throughout a block. In addition, each variant was presented twice and in randomized order without replacement.

Scheduling of the variant-to-base and base-to-variant test blocks. Participants were presented with eight test blocks that contained stimuli in the A domain and then with eight more blocks that contained stimuli from the B domain. For stimuli in a given domain, the variant-to-base and base-to-variant test blocks alternated. Thus, each variant was presented eight times in each test format.

Class width for variants used as sample stimuli. When the variant-to-base tests were conducted, variants were considered to be members of the same perceptual class if each of them produced the selection of the anchor-stimulus comparison at the same end of the domain on at least 88% of the test trials. The boundary stimulus for that class was defined as the variant farthest away from the anchor stimulus. The midpoint stimulus for a class was the variant with a value equidistant between the anchor and the boundary stimuli. Thus, the results of the variant-to-base tests established the unit values for the midpoint and boundary stimuli that were used subsequently as samples.

Class width for variants used as comparison stimuli. When the base-to-variant tests were conducted, the members of a perceptual class were identified as the variants that were selected in the presence of the anchor stimulus on at least 88% of the test trials. The boundary stimulus for that class was the variant farthest removed from the anchor stimulus of the same class. The midpoint stimulus for a class was the variant with a value equidistant between the anchor and the boundary stimuli. Thus, the results of the base-to-variant tests established the unit values for the midpoint and boundary stimuli that were used subsequently as comparisons.

Phase 4a: Establishment of cross-class conditional discriminations. After the emergence of the four perceptual classes A1′, A2′, B1′, and B2′, the A1′ and B1′ classes were potentially linked by the establishment of conditional discriminations between the anchors of both classes (A1a→B1a), and the boundaries of both classes (A1b→B1b). Likewise, the A2′ and B2′ classes were potentially linked by the establishment of conditional discriminations A2a→B2a and A2b→B2b. The Aa–Ba relations were established on trials in which the samples were either A1a or A2a, and the comparisons were always B1a and B2a. For example, given the presentation of A2a as the sample, the selection of B2a as the matching comparison produced the word RIGHT on the computer screen. The selection of B1a produced the word WRONG. The Ab–Bb relations were established on trials in which the sample stimuli were either A1b or A2b and the comparisons were always the pair of stimuli B1b and B2b. Thus, given A2b, the selection of B2b produced the word RIGHT, and the selection of B1b produced the word WRONG.

The cross-class conditional discriminations are listed symbolically in Table 1. The actual stimuli were members of Domains A and B. Each block contained 32 trials, 8 each of the four A–B configurations depicted in the Baseline portion of Table 1, specifically, the two rows labeled LPC (linked perceptual class). These trials were presented in a randomized order without replacement. Each block was repeated with informative feedback on each trial until all trials produced correct comparison selections, i.e., until performance reached the mastery criterion of 100% accuracy. A new block was introduced at that point. This continued until the participant demonstrated 100% accuracy across three consecutive blocks. Achieving this performance criterion defined the end of the acquisition condition of the phase. It was followed by the maintenance condition in which the percentage of trials in a block that produced feedback was reduced as long as 100% accuracy was maintained. The maintenance condition ended when a participant responded with 100% accuracy in a block that provided no feedback.

Phase 4b: Testing for symmetry in the cross-class conditional discriminations. Once the cross-class conditional discriminations were maintained in the absence of feedback, the symmetrical properties of the stimuli in each relation were evaluated with the presentation of the symmetry probes B1a→A1a, B1b→A1b, B2a→A2a, and B2b→A2b. These

Table 1

A symbolic representation of the stimuli used in the cross-class conditional discriminations trained in Experiments 1, 2, and 3 in the Baseline and Symmetry components.

			Class 1			Class 2		
Trial Type	Class (Exp #)	Sa—>Co	Sa	Co+	Co−	Sa	Co+	Co−
Baseline	LPC (1, 2, 3)	Aa—>Ba	A1a	B1a	B2a	A2a	B2a	B1a
		Ab—>Bb	A1b	B1b	B2b	A2b	B2b	B1b
	PEGEC (1, 2)	Ba—>C	B1a	C1	C2	B2a	C2	C1
	FEGEC (3)	Ba—>Ca	B1a	C1a	C2a	B2a	C2a	C1a
		Bb—>Cb	B1b	C1b	C2b	B2b	C2b	C1b
Symmetry	LPC (1, 2, 3)	Ba—>Aa	B1a	A1a	A2a	B2a	A2a	A1a
		Bb—>Ab	B1b	A1b	A2b	B2b	A2b	A1b
	PEGEC (1, 2)	Ca—>Ba	C1a	B1a	B2a	C2a	B2a	B1a
		Cb—>Bb	C1b	B1b	B2b	C2b	B2b	B1b
	FEGEC (3)	Ca—>Ba	C1a	B1a	B2a	C2a	B2a	B1a
		Cb—>Bb	C1b	B1b	B2b	C2b	B2b	B1b

Note: In columns Class 1 and Class 2, each row indicates the stimuli used to establish the conditional discriminations. Each stimulus is defined by an initial capital letter that refers to a unique stimulus, by a numeral that represents class membership, and by a lower-case letter that designates the anchor (a) and boundary (b) value of the stimulus. In Experiments 1 and 2, the relations to be trained were Aa–Ba, Ab–Bb, and Ba–C. In Experiment 3, the relations to be trained were Aa–Ba, Ab–Bb, Ba–Ca, and Bb–Cb. For column Class, abbreviations LPC = linked perceptual class, PEGEC = partially elaborated generalized equivalence class, and FEGEC = fully elaborated generalized equivalence class. Experiment numbers appear in parentheses. Sa = sample and Co = comparisons. Co+ = correct comparison and Co− = incorrect comparison.

trials were presented in blocks that also contained the cross-class conditional discriminations. Each block consisted of 32 trials, 4 each of the four A–B baseline relations and 4 each of the B–A symmetry relations that can be derived from the baseline relations. The symmetry trials are listed in the Symmetry portion of Table 1. All trials in a block were presented without feedback and in a randomized order without replacement. To advance to the next phase participants had to respond with at least 94% accuracy on the symmetry test block. If participants did not reach at least 94% accuracy within two blocks, the more recent block was repeated with feedback for all trials until the accuracy criterion was met.

Phase 5: Cross-class tests for the emergence of linked perceptual classes. Participants were presented with a battery of 18 different cross-class probes that consisted of all pairwise combinations of the anchor, midpoint, and boundary stimuli in the two nominally linked perceptual classes. The specific stimuli included in each probe are listed in Table 2.

Nine of the probes were in an A′–B′ format. Each probe contained a stimulus from an A′ class as the sample, with a pair of stimuli from the B′ classes as the comparisons. All trials also included the neither comparison. For example, an Aa–Bb probe consisted of an A1a or A2a stimulus presented as the sample and the B1b and B2b stimuli as comparisons along with the neither comparison. The nine re-

Table 2

Symbolic representation of the cross-class probe trials used to evaluate the formation of linked perceptual classes and partially elaborated generalized equivalence classes.

			Class 1 probes				Class 2 probes			
Test Block	Row #.	Probes in Block	Sa	Co+	Co−	Co−	Sa	Co+	Co−	Co−
Aamb–Aa	1	Aa—>Ba	$A1^{a}$	$B1^{a}$	$B2^{a}$	NC	$A2^{a}$	$B2^{a}$	$B1^{a}$	NC
	2	Am–>Ba	$A1^{m}$	$B1^{a}$	$B2^{a}$	NC	$A2^{m}$	$B2^{a}$	$B1^{a}$	NC
	3	Ab—>Ba	$A1^{b}$	$B1^{a}$	$B2^{a}$	NC	$A2^{b}$	$B2^{a}$	$B1^{a}$	NC
Aamb–Bm	4	Aa—>Bm	$A1^{a}$	$B1^{m}$	$B2^{m}$	NC	$A2^{a}$	$B2^{m}$	$B1^{m}$	NC
	5	Am–>Bm	$A1^{m}$	$B1^{m}$	$B2^{m}$	NC	$A2^{m}$	$B2^{m}$	$B1^{m}$	NC
	6	Ab—>Bm	$A1^{b}$	$B1^{m}$	$B2^{m}$	NC	$A2^{b}$	$B2^{m}$	$B1^{m}$	NC
Aamb–Bb	7	Aa—>Bb	$A1^{a}$	$B1^{b}$	$B2^{b}$	NC	$A2^{a}$	$B2^{b}$	$B1^{b}$	NC
	8	Am–>Bb	$A1^{m}$	$B1^{b}$	$B2^{b}$	NC	$A2^{m}$	$B2^{b}$	$B1^{b}$	NC
	9	Ab—>Bb	$A1^{b}$	$B1^{b}$	$B2^{b}$	NC	$A2^{b}$	$B2^{b}$	$B1^{b}$	NC
Bamb–Aa	10	Ba—>Aa	$B1^{a}$	$A1^{a}$	$A2^{a}$	NC	$B2^{a}$	$A2^{a}$	$A1^{a}$	NC
	11	Bm–>Aa	$B1^{m}$	$A1^{a}$	$A2^{a}$	NC	$B2^{m}$	$A2^{a}$	$A1^{a}$	NC
	12	Bb—>Aa	$B1^{b}$	$A1^{a}$	$A2^{a}$	NC	$B2^{b}$	$A2^{a}$	$A1^{a}$	NC
Bamb–Am	13	Ba–>Am	$B1^{a}$	$A1^{m}$	$A2^{m}$	NC	$B2^{a}$	$A2^{m}$	$A1^{m}$	NC
	14	Bm->Am	$B1^{m}$	$A1^{m}$	$A2^{m}$	NC	$B2^{m}$	$A2^{m}$	$A1^{m}$	NC
	15	Bb–>Am	$B1^{b}$	$A1^{m}$	$A2^{m}$	NC	$B2^{b}$	$A2^{m}$	$A1^{m}$	NC
Bamb–Ab	16	Ba–> Ab	$B1^{a}$	$A1^{b}$	$A2^{b}$	NC	$B2^{a}$	$A2^{b}$	$A1^{b}$	NC
	17	Bm->Ab	$B1^{m}$	$A1^{b}$	$A2^{b}$	NC	$B2^{m}$	$A2^{b}$	$A1^{b}$	NC
	18	Bb–> Ab	$B1^{b}$	$A1^{b}$	$A2^{b}$	NC	$B2^{b}$	$A2^{b}$	$A1^{b}$	NC
Bamb–C	1	Ba—>C	$B1^{a}$	C1	C2	NC	$B2^{a}$	C2	C1	NC
	2	Bm—>C	$B1^{m}$	C1	C2	NC	$B2^{m}$	C2	C1	NC
	3	Bb—>C	$B1^{b}$	C1	C2	NC	$B2^{b}$	C2	C1	NC
C–Bamb	4	C—>Ba	C1	$B1^{a}$	$B2^{a}$	NC	C2	$B2^{a}$	$B1^{a}$	NC
	5	C—>Bm	C1	$B1^{m}$	$B2^{m}$	NC	C2	$B2^{m}$	$B1^{m}$	NC
	6	C—>Bb	C1	$B1^{b}$	$B2^{b}$	NC	C2	$B2^{b}$	$B1^{b}$	NC
Aamb–C	7	Aa—>C	$A1^{a}$	C1	C2	NC	$A2^{a}$	C2	C1	NC
	8	Am—>C	$A1^{m}$	C1	C2	NC	$A2^{m}$	C2	C1	NC
	9	Ab—>C	$A1^{b}$	C1	C2	NC	$A2^{b}$	C2	C1	NC
C–Aamb	10	C—>Aa	C1	$A1^{a}$	$A2^{a}$	NC	C2	$A2^{a}$	$A1^{a}$	NC
	11	C—>Am	C1	$A1^{m}$	$A2^{m}$	NC	C2	$A2^{m}$	$A1^{m}$	NC
	12	C—>Ab	C1	$A1^{b}$	$A2^{b}$	NC	C2	$A2^{b}$	$A1^{b}$	NC

Note. Each row lists the trial types in the cross-class probes for Class 1 and Class 2. Within a row, both probes shared the same set of comparisons, but the positive comparison was different for each class. Superscripts a, b, and m = anchor, midpoint, and boundary stimuli, respectively. NC = the neither comparison. Each probe is indicated in a separate row. Rows 1–18 (top) list the probes used to evaluate the emergence of the linked perceptual classes. Rows 1–12 (bottom) list the probes used to evaluate the emergence of partially elaborated generalized equivalence classes.

maining probes were in a B′–A′ format. In each, a stimulus from a B′ class was presented as a sample and stimuli from the A′ classes as comparisons. For example, in a Bb–Aa probe, a B1b or B2b stimulus would be presented as the sample and the A1a and A2a stimuli as the comparisons along with the neither comparison.

The 18 cross-class probes were presented in a systematic order—the 18/1 PRGM test (Fields et al., 2005). In this test, each of the probes (18) was presented in a separate test block (1) and the various probe types were introduced in a highly programmed progression (PRGM). Prior research has shown that its use maximizes the likelihood of forming linked perceptual classes (Fields et al., 2005). All nine A′–B′ probes were presented before the nine B′–A′ probes. When the A′–B′ probes were presented, the anchor, midpoint, and boundary stimuli from the A1′ and A2′ classes were the samples in the first, second, and third test blocks, respectively (see Table 2). All three of these blocks contained the anchor stimuli from the B1′ and B2′ classes as the comparisons. The anchor, midpoint, and boundary stimuli from the A1′ and A2′ classes were the sample stimuli in the fourth, fifth, and sixth test blocks, respectively, but the midpoint stimuli from the B1′ and B2′ classes served as comparisons. Finally, the anchor, midpoint, and boundary stimuli from the A1′ and A2′ classes were the sample stimuli in the seventh, eighth, and ninth test blocks, respectively and boundary stimuli from the B1′ and B2′ classes served as the comparisons. Thus the symbolic representation of this entire sequence of probe presentations is: Aa–Ba, Am–Ba, Ab–Ba, Aa–Bm, Am–Bm, Ab–Bm, Aa–Bb, Am–Bb, and Ab–Bb. A different sequence was presented during test blocks 10–18 where the B′ stimuli served as samples and the A′ stimuli served as comparisons. The symbolic representation of this sequence of probe presentations is: Ba–Aa, Bm–Aa, Bb–Aa, Ba–Am, Bm–Am, Bb–Am, Ba–Ab, Bm–Ab, and Bb–Ab.

The probes were presented in blocks consisting of 16 trials. On 8 of the trials, the Class 1 stimulus was presented as the sample. On the remaining 8 trials, the Class 2 stimulus served as the sample. In addition, the locations of the comparisons were randomized and balanced across the trials. The 16 trials were presented in a randomized sequence without replacement. Class-consistent responding on at least 7 of the 8 trials (88%) indicated the emergence of a relation between the sample and comparison from one nominally linked perceptual class. A linked perceptual class was considered to have emerged when class-consistent responding of at least 88% accuracy was observed for at least 17 of the 18 probe types. One participant who did not meet this criterion for linked perceptual class formation was dismissed from the experiment.

Phase 6: Expansion of class size (Ba→C training). Participants who formed linked perceptual classes were given additional training to establish conditional discriminations between the anchor stimulus of a B′ class and a new C stimulus (B1a→C1 and B2a→C2). The contingencies and criteria used were the same as those described in Phase 4. Each block consisted of 16 trials, 8 trials for each C–Ba relation. After these conditional discriminations were trained, participants were presented with (C→Ba) probes to assess the symmetrical properties of the Ba→C conditional discriminations as in Phase 4b. The trial types used in this phase are listed in Table 1 under Baseline PEGEC (partially elaborated generalized equivalence class).

Phase 7: Testing for partially elaborated generalized equivalence classes (A′–B′–C). After the formation of the Ba–C conditional discriminations in Phase 6, the participants were presented with 12 different cross-class probes that consisted of the trained relations and all the remaining relations that could be derived from the stimuli in the A′ and B′ classes in combination with the corresponding C stimuli. The trials presented in each probe are listed in detail in Table 2 (the final 12 rows). Each block consisted of 16 trials. On 8 of the trials, the Class 1 stimulus was presented as the sample, and on the other 8 trials the Class 2 stimulus was presented as the sample. The probes were presented in the following order: Ba–C, Bm–C, Bb–C, C–Ba, C–Bm, C–Bb, Aa–C, Am–C, Ab–C, C–Aa, C–Am, and C–Ab. This schedule—the 12/1-PRGM test—used the same logic that characterized the 18/1-PRGM test and provided an evaluation of the expansion of linked perceptual classes to partially elaborated generalized equivalence classes. The criterion for this expansion was class-consistent responding (88% or greater) for at least 11 of the 12 probes.

Sessions and phases. Session 1 for all participants consisted of Phases 1 and 2. Session 2 consisted of Phases 3 and 4, which evaluated the emergence of linked perceptual classes. Participants were then randomly assigned to one of two groups, which differed in terms of the time that elapsed between the emergence of linked perceptual classes and their expansion to partially elaborated generalized equivalence classes. In Group 1, Phases 5–7 were conducted during Session 2 immediately after the completion of Phases 3 and 4. In Group 2, Session 2 was terminated at the completion of Phase 4. In Session 3, which occurred 3–7 days thereafter, these participants completed Phases 5–7.

Results

Perceptual Class Identification

The stimuli included in the A1′, A2′, B1′, and B2′ classes were identified using the generalization gradients collected in Phase 3 of the experiment. Contiguous stimuli along a continuum function as members of a perceptual class when they produce common responding in the absence of direct training. When a variant-to-base test is conducted, a class consists of the stimulus variants that occasion the selection of a common stimulus with similar high probability in the absence of training. When a base-to-variant test is conducted, a class consists of the stimulus variants that are selected with the same high probability in the presence of a given stimulus, again in the absence of training.

Figure 3 shows generalization data for the B1′ and B2′ classes for Participant 4, which were representative of the gradients produced by all participants. With the variant-to-base procedure the widths of the perceptual classes were identified with the data presented in the three graphs in the left column. As seen in the top graph the anchor stimulus in the B2′ class (SAT-500) was selected on at least 88% of trials in the presence of variants SAT-340 through SAT-500. Thus, those variants functioned as members of the B2′ class, with SAT-340 as the boundary stimulus. A similar pattern was produced by the variants at the other end of Domain B and defined the members of the B1′ class. As seen in the bottom graph the anchor stimulus in the B1′ class (SAT-000) was selected on at least 88% of trials in the presence of variants SAT-000 through SAT-170. Thus, those variants were considered to be members of the B1′ class, with SAT-170 as its boundary.

When the base-to-variant procedures were used, the width of the B1′ class was identified using the data presented in the graphs in the center column. During these tests, each trial involved the presentation of SAT-000 as the sample, with a different variant as one comparison and SAT-500 and the neither comparison as the other comparisons on all trials. The bottom graph shows that the variants from SAT-000 to SAT-170 were selected on at least 88% of trials in the presence of SAT-000, the anchor stimulus in the B1′ class. Thus, those variants functioned as members of the B1′ class, with SAT-170 as its boundary.

The width of the B2′ class in the base-to-variant procedure was identified using the data presented in the graphs in the right column. During this test, each trial involved the presentation of SAT-500 as the sample, with a different variant as one comparison and the SAT-000 and the neither comparison as the other comparisons. The top graph shows that the variants from SAT-340 to SAT-500 were selected on at least 88% of trials in the presence of SAT-500. Thus, those variants were members of the B2′ class, with SAT-340 as its boundary.

Functional Independence of Perceptual Classes

The responses evoked by the stimuli between the boundary stimuli of the two potential classes in a domain can be used to determine whether one or two classes emerged in that domain. If the selection of the stimuli from one potential class in a domain is complemented by the selection of stimuli from the other potential class in the same domain, either two classes have emerged in the domain, or only one class has emerged and the other stimuli in the domain are acting as a default: although they all evoke a common response, the stimuli do not function as members of another class (Innis et al., 1998). On the other hand, if a decline in responding to the stimuli in each potential class at their boundaries within a domain is accompanied by a complementary increase in the selection of the neither comparison, the only conclusion that can be reached is that two functionally independent classes have emerged in that

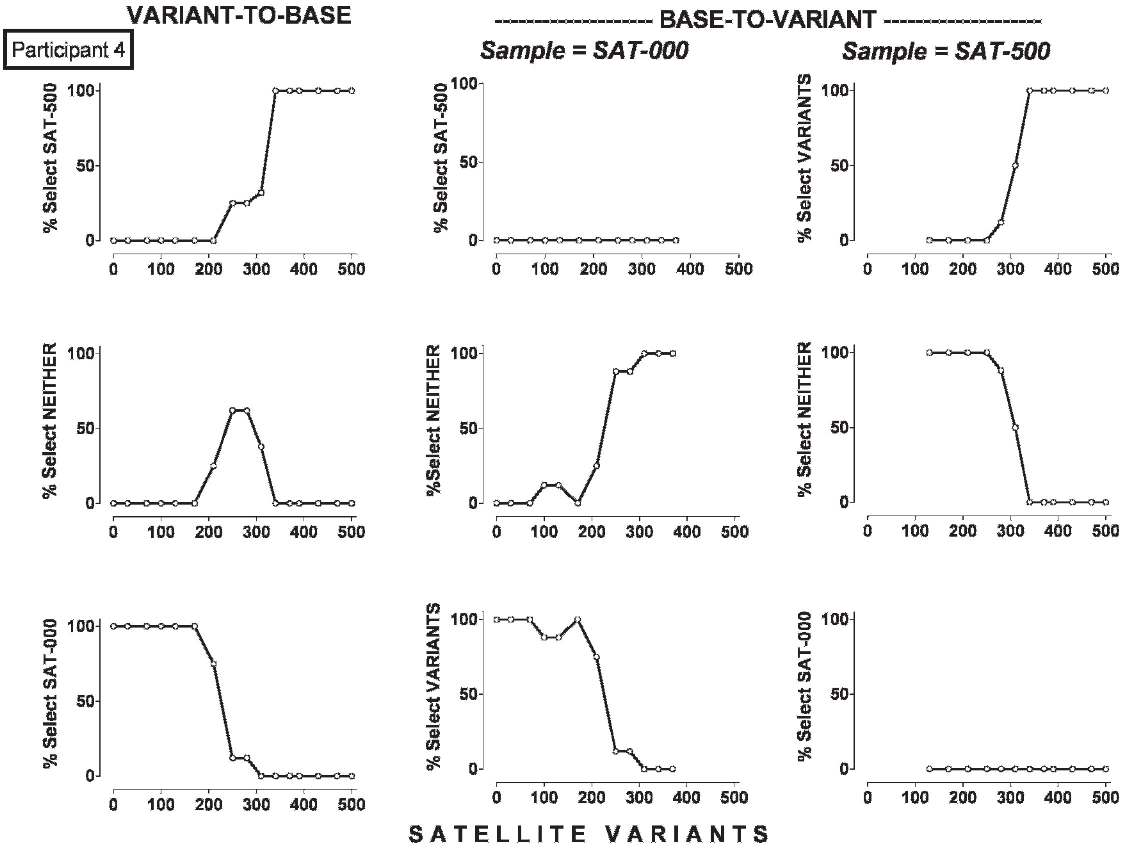

Fig. 3. The results of the variant-to-base and base-to-variant tests for Participant 4 in Phase 3 of Experiment 1. The three graphs in the left column indicate results of the variant-to-base tests and plot the percentage of selecting SAT-000 (bottom panel), the neither comparison (middle panel), and SAT-500 (top panel) as functions of the value of the variants presented as samples. The results of the base-to-variant tests are presented in the two remaining columns. The graphs in the middle column plot the likelihoods of selecting the SAT variants (bottom panel), the neither comparison (middle panel), or the negative comparison (top panel) when SAT-000 was the sample as functions of the value of the variants presented as comparisons. The right column plots likelihoods of selecting the variants (top panel), the neither comparison (middle panel), or the negative comparison (bottom panel) when SAT-500 was the sample.

domain (Fields & Reeve, 2001; Fields et al., 2002b; Wasserman, et al., 1988).

When variant-to-base procedures were used (see Figure 3, left column), as the variants moved below the boundary of the B2′ class (SAT-340), the selection of SAT-500 declined systematically (top graph) and was accompanied by a complementary increase in the selection of the neither comparison (middle graph) at that point. In contrast, there was no selection of the SAT-000 comparison until SAT-170 (bottom graph). In a similar manner, as the variants moved above the boundary of the B1′ (SAT-170) class, the selection of SAT-000 declined systematically and was accompanied by a complementary increase in the selection of the neither comparison (bottom and middle graphs). In contrast, there were no selections of SAT-500 (top graph).

When a base-to-variant procedure was used with SAT-000 as the sample (see Figure 3, middle panel), a decrease in the selection of variants greater than SAT-170 (see bottom graph) was accompanied by an increase in the selection of the neither comparison (see middle graph), but no selection of SAT-500 (top graph). When SAT-500 was the sample (right panel), a rapid decline in the selection of variants less than SAT-340 (top graph) was accompanied by a complementary increase in

Table 3

Boundary stimuli in the perceptual classes A1′, A2′, B1′, and B2′ as measured with variant-to-base (VB) and base-to-variant (BV) tests in Experiment 1.

	Perceptual Class							
	A1′		A2′		B1′		B2′	
Participant	VB	BV	VB	BV	VB	BV	VB	BV
2	18	18	40	40	170	100	310	340
1	18	21	40	40	170	170	340	340
3	12	09	40	40	170	100	370	370
4	15	18	37	37	170	170	340	340
5	15	18	34	34	170	210	370	370
Mean	16	17	38	38	170	150	346	352
Min–Max[1]	00	00	50	50	000	000	500	500

Note. Means were rounded to the nearest whole number.
[1] Minimum and maximum values assigned to the respective endpoint stimuli in each domain.

the selection of the neither comparison (middle graph) and no selection of SAT-000 (bottom graph).

Overall, the decreases in the selection of stimuli from one class were accompanied by a complementary increase in the selection of the neither comparison rather than an increase in the selection of variants from the other end of the domain. This finding supports the view that the A1′, A2′, B1′ and B2′ perceptual classes were functionally independent of each other.

Boundary Stimuli and Widths of Perceptual Classes

The width of a perceptual class was defined by the difference in the values of its anchor and boundary stimuli. Since the values of the anchors were fixed, the width of each class effectively was indexed by the values of boundary stimuli. The values obtained from the variant-to-base and base-to-variant procedures for each perceptual class and each participant are listed in Table 3. For Domain A, which had endpoint values of 0 and 50 units, the boundary stimuli of the A1′ and A2′ classes averaged 17 and 38 units, respectively, and were separated by an average of 21 units. Thus, the average widths for the A1′ and A2′ classes were 17 and 12 units, respectively. For Domain B, which had endpoint values of 0 and 500 units, the boundary stimuli of the B1′ and B2′ classes averaged 160 and 349 units, respectively, and were separated by an average of 189 units. The average widths for the B1′ and B2′ classes were 160 and 151 units, respectively.

Discriminability of Stimuli in Perceptual Classes

For a set of stimuli to act as a perceptual class, there should be generalization among the stimuli in a class, and some class members must be discriminable from each other (Fields et al., 2002b; Fields & Reeve, 2001; Keller & Schoenfeld, 1950; Lashley & Wade, 1946; Lea, 1984; Wasserman et al., 1988). In this experiment, the discriminability of the stimuli in a perceptual class was measured by considering the response speeds occasioned by the anchor, midpoint and boundary stimuli (Fields et al., 2002b; Fields et al., 2005; Spencer & Chase, 1996). Response speed is the inverse of the latency that separated the onset of the set of comparison stimuli to the selection of one of the comparisons. For a given stimulus variant, there were no systematic differences in response speed across participants, test type, domain, or class. Thus, the data were collapsed across these factors, and mean response speeds were computed for the anchor, midpoint, and boundary stimuli, respectively. Mean response speeds were fastest for the anchor stimuli (0.84 responses/s), slower for the midpoint stimuli (0.7 responses/s), and slowest for the boundary stimuli (0.41 responses/s). A 1 $\times$ 3 analysis of variance confirmed that these differences in response speeds were not random, $F(2) = 44.89$, $p < .0001$. Newman-Keuls post-hoc tests of pairwise comparisons showed that significantly different response speeds were produced by the anchor and midpoint stimuli ($q = 4.096$, $p < .01$), the midpoint and boundary stimuli ($q = 9.001$, $p < .001$), and the anchor and boundary stimuli

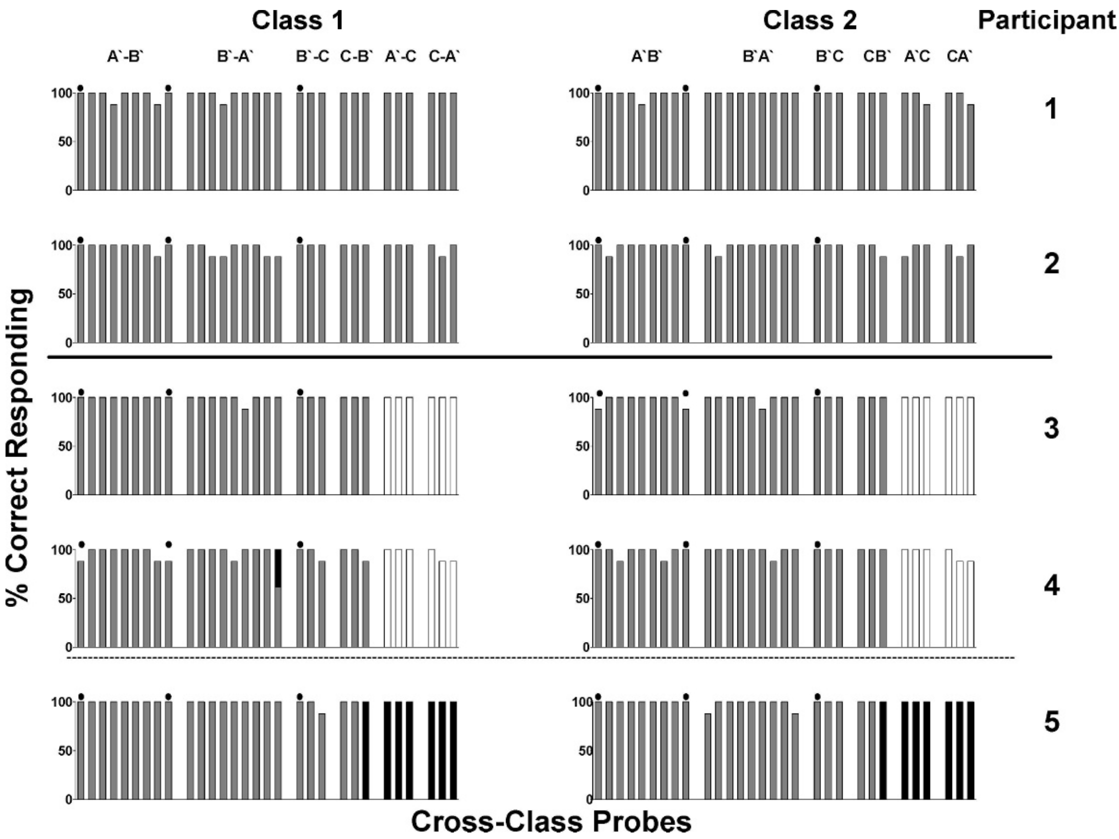

Fig. 4. Results of Experiment 1 for the participants in Groups 1 and 2. The figure shows the percentage of class-consistent comparisons that were selected for each probe used to evaluate the formation of linked perceptual classes and partially elaborated generalized equivalence classes for each participant in Experiment 1. The panels on the left and right represent the data for classes 1 and 2, respectively. The panels in a given row are for one participant. The panels above and below the heavy solid horizontal line are for participants in Groups 1 and 2, respectively. In each panel, the 30 bars portray the performances occasioned by each of the probes used to evaluate the formation of a linked perceptual class or a partially elaborated generalized equivalence class. The first and second sets of nine bars are for A′–B′ and B′–A′ probe types, respectively. The next four sets of three bars are B′–C, C–B′, A′–C, and C–A′ probe types, respectively. The headers at the top of the figure indicate the bars that correspond to the probes of a given type. The letter pairs that appear beneath bars on the abscissa stipulate the stimuli that served as the sample and comparisons. For example, mb indicates a Bm–Ab probe in which the sample was the midpoint stimulus from the B class presented in combination with the boundary stimuli from the corresponding A class as comparisons. The gray portion of a bar indicates the percentage of trials using a given probe type that produced selection of the class-consistent comparison. The white portion of a bar indicates the percentage of trials using a given probe type that produced the selection of the comparison from a perceptual class other than the class represented by the sample, i.e., the negative comparison also represented as Co-. The black portion of a bar indicates the percentage of trials using a given probe type that produced the selection of the neither comparison. A dot above a bar indicates a trained relation.

(q = 13.10, $p < .001$). Thus, the anchor, midpoint, and boundary stimuli were discriminable from each other.

Emergence of Linked Perceptual Classes

Figure 4 show results from each participant in the remaining phases of Experiment 1. Data for each participant are presented in a given row, with the results from classes 1 and 2 appearing in the left and right columns, respectively. Each panel contains 30 bars. The 18 bars in the left half of each panel show the percentage of correct responses on the nine A′–B′ and nine B′–A′ probe trials that were used to evaluate the emergence of linked perceptual classes. The 12 bars in the right half of each panel show the percentage of correct responses to the B′–C, C–B′, A′–C, and C–A′

probes that were used to evaluate the emergence of partially elaborated generalized equivalence classes.

The conditions used to produce linked perceptual classes did not differ procedurally for the participants in each group. As the left half of each panel demonstrates, all of the participants showed criterion levels of responding to at least 17 of the 18 cross-class probes, thereby demonstrating the rapid emergence of linked perceptual classes 1 and 2.

Emergence of Partially Elaborated Generalized Equivalence Classes

The two groups differed procedurally when the linked perceptual classes were expanded to partially elaborated generalized equivalence classes. Thus, the data were treated separately for participants in each group. The results of the expansion were presented in the two top rows of Figure 4 for 2 of the participants in Group 1, Participant 1 and Participant 2. Both met the criterion of class-consistent performance for at least 11 of the 12 probe trials. These performances documented the rapid expansion of linked perceptual classes to partially elaborated generalized equivalence classes and also constituted the first laboratory-based demonstration of the formation of partially elaborated generalized equivalence classes.

The results of class expansion for the 3 participants in Group 2 are presented in the bottom three rows of Figure 4. Participant 3, 4, and 5 responded in a class-consistent manner to 5 or 6 of the 12 probe trials. Thus, these participants did not show the expansion of linked perceptual classes to partially elaborated generalized equivalence classes. Within each class, each participant responded in a class-consistent manner to the B′–C probes, which provided a generalization test of the trained Ba–C conditional discriminations. They also responded in a class-consistent manner to most of the C–B′ probes, which demonstrated the generalization of symmetry. In contrast, they did not respond in a class-consistent manner to the A′–C and C–A′ probes, which tested the generalization of transitivity and equivalence, respectively.

Discussion

All 5 participants in the experiment showed the immediate emergence of linked perceptual classes. Thereafter, 2 of the participants formed partially elaborated generalized equivalence classes. This was the first laboratory demonstration of the formation of partially elaborated generalized equivalence classes.

The 3 remaining participants formed linked perceptual classes, but they did not go on to form partially elaborated generalized equivalence classes. Although they responded in a class-consistent manner during the generalization tests of symmetry (B′–A′ and C–B′), they made consistent errors during the generalization tests of transitivity (A′–C) and of equivalence (C–A′). Experiment 2 was designed to explore a variable that we considered responsible for these participants' failure to form the partially elaborated generalized equivalence classes in Experiment 1.

EXPERIMENT 2

In Experiment 1, the emergence of partially elaborated generalized equivalence classes was inversely related to the delay between the emergence of the linked perceptual classes, and the procedures that were used for their expansion. The procedure was successful when the training that was used to expand linked perceptual classes to partially elaborated generalized equivalence classes took place immediately after the emergence of linked perceptual classes.

In contrast, successful expansion did not occur when 3 to 7 days separated the emergence of linked perceptual classes from expansion training. The expansion session (the third session) began with the training of the Ba–C relations, but neither the strength of the conditional discriminations that linked the two perceptual classes A′ and B′, or the integrity of the linked perceptual classes themselves was reevaluated before the expansion procedures were introduced. The failure of expansion, then, could be attributed to weakened A′–B′ conditional discriminations, or linked perceptual classes as a consequence of the delay.

In Experiment 2, half of the participants were given the training and testing needed to confirm the emergence of linked perceptual classes and then were exposed to the training needed to expand those classes to partially elaborated generalized equivalence classes within the same session, as in Experiment 1. For the remaining participants linked percep-

Table 4

Boundaries of perceptual classes A1′, A2′, B1′, and B2′ measured with variant-to-base (VB) and base-to-variant (BV) tests for participants in Groups 1 and 2 in Experiment 2.

		Perceptual Class							
		A1′		A2′		B1′		B2′	
Group	Participant	VB	BV	VB	BV	VB	BV	VB	BV
1	6	18	18	37	37	170	130	340	340
	7	18	21	34	37	170	210	340	370
	8	21	25	40	34	130	250	340	340
	9	15	18	40	34	170	210	310	280
	10	15	15	37	43	170	170	340	310
2	11	18	21	40	34	100	100	340	390
	15	21	21	34	34	170	170	340	340
	12	15	15	37	34	170	210	340	340
	14	18	18	40	34	170	170	340	340
	13	09	15	40	40	210	170	340	340
	Mean	**17**	**19**	**38**	**36**	**163**	**179**	**337**	**339**
	Min–Max[1]	**00**	**00**	**50**	**50**	**000**	**000**	**500**	**500**

[1] Minimum and maximum values assigned to the respective endpoint stimuli on each domain.

tual classes emerged in one session. One week later the participants received the training necessary to expand the linked perceptual classes to partially elaborated generalized equivalence classes. Before expansion training, however, probes were used to confirm that the conditional discriminations that characterized the linked perceptual classes and their symmetrical relations remained intact. Contra Experiment 1, an increase in the likelihood of forming partially elaborated generalized equivalence classes would indicate that such a confirmatory procedure was responsible for that emergence. It would also show that the mere passage of time was not responsible for the previous failure of class expansion. Rather, it stemmed from changes in the strength of the conditional discriminations.

Method

Participants

Ten college students participated in Experiment 2. Each participant was drawn from the same participant pool that had been used to obtain participants for Experiment 1, though none of the participants in Experiment 2 had also participated in Experiment 1. Five participants were randomly assigned to each of Groups 1 and 2.

Apparatus and Stimuli

The apparatus and stimuli were the same as those used in Experiment 1.

Procedure

The procedures were the same as in Experiment 1 with one addition. For participants in Group 2, Session 3 began 7 days after the the session in which linked perceptual classes emerged. It began with a test of the Aa–Ba and Ab–Bb conditional discriminations in the absence of informative feedback. The participants were presented with one test block that contained 32 trials, 8 each of the four A–B baseline relations. If participants performed with 100% accuracy, symmetry was tested with Ba–Aa and Bb–Ab probes, as in Phase 4a in Experiment 1. On the other hand, if the participants did not perform with 100% accuracy on the test of conditional discriminations, they were retrained using the procedures described in Phase 4 of Experiment 1. When the Aa–Ba and Ab–Bb trials produced 100% accuracy with 0% feedback, symmetry was tested. Once participants achieved the mastery criterion for symmetry, they received Ba–C training and were tested for the emergence of partially elaborated generalized equivalence classes, as described in Phase 7 of Experiment 1.

Results

Boundary Values and Widths of the A′ and B′ Classes

Table 4 lists the boundary values of the A′ and B′classes that were measured in Phase 3 of Experiment 2 using variant-to-base and base-

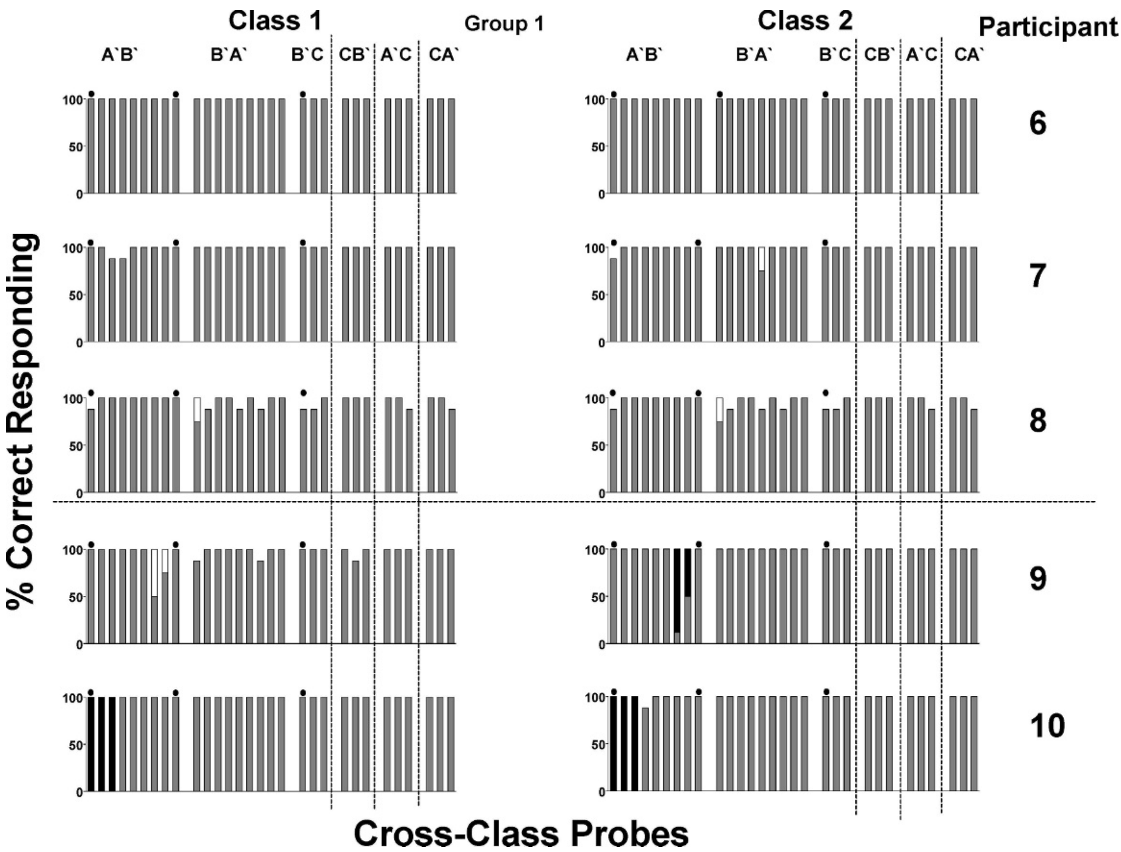

Fig. 5. Probe data for participants in Experiment 2, Group 1. The format is the similar to that used in Figure 4 with one exception. The panels above and below the dashed horizontal line contain data for the participants who showed immediate or delayed emergence of the linked perceptual classes, respectively.

to-variant procedures. For Domain A, which had endpoint values of 0 and 50 units, the boundary stimuli of the A1′ and A2′ classes averaged 18 and 37 units, respectively, and thus were separated by an average of 19 units. The mean widths for the A1′ and A2′ classes were 18 and 13 units, respectively. For Domain B, which had endpoint values of 0 and 500 units, the boundary stimuli of the B1′ and B2′ classes averaged 171 and 338 units, respectively, and were separated by an average of 167 units. The mean widths for the B1′ and B2′ classes were 171 and 162 units, respectively.

Discriminability of Variants in a Perceptual Class

Mean response speeds were fastest for the anchors (1.09 responses/s), slower for the midpoint stimuli (0.87 responses/s) and slowest for the boundary stimuli (0.56 response/s). A 1 × 3 analysis of variance confirmed that these differences in response speed could not be attributed to random processes, $F(2) = 53.17$, $p < .0001$. Newman-Keuls post-hoc tests of pairwise comparisons showed that significantly different response speeds were produced by the anchor and midpoint stimuli ($q = 5.891$, $p < .001$), the midpoint and boundary stimuli ($q = 8.608$, $p < .001$), and the anchor and boundary stimuli ($q = 14.50$, $p < .001$). Thus, the anchor, midpoint, and boundary stimuli in each perceptual class were discriminable from each other.

Emergence of Linked Perceptual Classes

Because the same procedures were used to establish linked perceptual classes for all participants, their data will be described together. Figures 5 and 6 depict the data for the participants in Experiment 2 using a format like that in Figure 4. Six participants

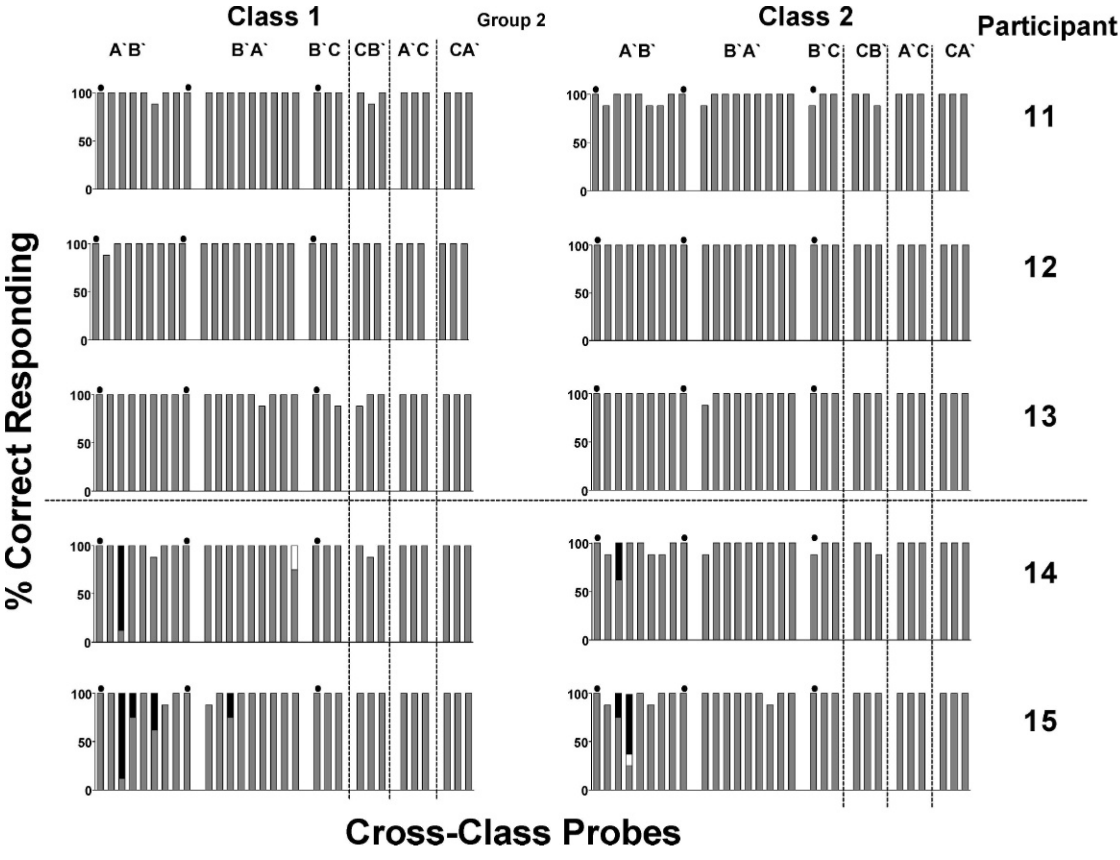

Fig. 6. Probe data for participants in Experiment 2, Group 2. The format is the same as in Figure 5.

(6, 7, and 8 in Group 1 and 11, 12, and 13 in Group 2) performed with at least 88% accuracy on at least 17 of the 18 cross-class probes. These 6 participants then showed the immediate emergence of both linked perceptual classes. The last 4 participants (9 and 10 in Group 1 and 14 and 15 in Group 2) did not meet the mastery criterion for the immediate emergence of both linked perceptual classes. In most cases, however, the errors occurred early in the testing sequence, which suggests that the emergence of the classes may have been delayed. This interpretation prompted us to move the participants forward in the experimental protocol.

Maintenance of Class-Linking Conditional Discriminations

For Group 2, Session 3 of Experiment 2 began with a test of the Aa–Ba and Ab–Bb conditional discriminations and symmetry. The results appear in Table 5. Participants 11, 12, and 15 performed with 100% accuracy on both tests. Although Participants 13 and 14 did not show 100% accuracy on the first Aa–Ba and Ab–Bb test block, their performances were close to the mastery criterion. Both participants then reacquired the conditional discriminations in one training block, maintained mastery during feedback reduction, and satisfied the symmetry criterion in one block.

Training of Ba–C Relations

The Ba–C conditional discriminations were acquired by the participants in Group 1 with a mean of 4.8 blocks and a range of 3–8 blocks. The 5 participants in Group 2 acquired the Ba–C conditional discriminations with a mean of 4.4 trials and a range of 3–6 blocks. Thus, the results were virtually the same for the acquisition of the Ba–C conditional discriminations when training occurred immediately after the formation of linked perceptual classes or a week thereafter as long as

Table 5

Results of initial testing, subsequent retraining, if required, and symmetry for participants in Group 2 of Experiment 2.

		Participants				
	% Trials w. Feedback	15	12	11	14	13
Initial Test	0	100	100	100	97	93
Retraining	100				100	100
Maintenance	75				100	100
	25				100	100
	0				100	88
						100
Symmetry	0	100	100	100	97	93
						100

Note. Each row presents data from a separate block of trials. The blocks were presented in the order designated by the successive rows.

additional training was provided as needed in the latter case. Once such training was completed, acquisition of the cross-linked conditional discriminations was rapid for all participants. All participants responded with 100% accuracy during the subsequent C–Ba symmetry test block.

Emergence of Partially Elaborated Generalized Equivalence Classes

Participants in Group 1 were presented with training and testing of the Ba–C conditional discriminations immediately after the formation of the linked perceptual classes in the same session. The emergence of the partially elaborated generalized equivalence classes was assessed with the presentation of the B′–C, C–B′, A′–C, and C–A′ probes. All 5 participants in Group 1 were successful on at least 11 of the 12 probes demonstrating the rapid emergence of partially elaborated generalized equivalence classes (see Figure 5).

For the 5 participants in Group 2, linked perceptual class formation occurred in one session and its expansion to partially elaborated generalized equivalence classes occurred one week later in Session 3. As already noted, Session 3 began with tests of the Aa–Ba and Ab–Bb conditional discriminations and symmetry. After mastery the Ba–C conditional discriminations was reestablished where needed, all participants were successful on all of the B′–C, C–B′, A′–C, and C–A′ probes (see Figure 6). These performances demonstrated the expansion of linked perceptual classes to partially elaborated generalized equivalence classes by all participants in Group 2.

Discussion

For 6 of the 10 participants in Experiment 2, both of the linked perceptual classes emerged in prompt fashion. For the remaining participants, the subsequent emergence of linked perceptual classes can only be inferred, as the participants were not reexposed to the linked perceptual class probes (see Fields et al., 2007). These same participants went on to form partially elaborated generalized equivalence classes. This required the emergence of the linked perceptual classes prior to the tests of their expansion to partially elaborated generalized equivalence classes. Thus, the emergence of the partially elaborated generalized equivalence classes support the inference that linked perceptual classes had been formed in the prior stages of Experiment 2.

Participants in Group 1 received training in Ba–C conditional discriminations immediately after the test for linked perceptual classes. For participants in Group 2, the training came 7 days later. In Experiment 1, the delay was 3–7 days. Under these conditions, none of the participants in Experiment 1 formed partially elaborated generalized equivalence classes. In contrast, all 5 participants in Experiment 2 formed them. The latter success is accounted for in terms of the testing and retraining for the emergence of linked perceptual classes that immediately preceded the expansion of linked cross-class discriminations to partially elaborated generalized equivalence classes.

EXPERIMENT 3

Experiments 1 and 2 identified variables that resulted in the reliable emergence of partially elaborated generalized equivalence classes and used testing procedures that tracked that emergence. Experiment 3 sought to establish fully elaborated generalized equivalence classes (A′–B′–C′) by conducting a systematic replication (Sidman, 1960, pp. 110–112) of the procedures used with participants in Group 2 of Experiment 2. First, two perceptual classes were induced among the stimuli in each of three pictorial domains, A1′, A2′, B1′, B2′, C1′, and C2′. Second, linked perceptual classes A1′–B1′ and A2′–B2′ were formed by the establishment of conditional discrimninations between the anchor stimuli of an A′ and B′ class and the boundary stimuli of the same A′ and B′ classes. Thereafter, conditional discriminations were established between the anchor stimuli of a B′ and C′ class and the boundary stimuli of the same B′ and C′ classes. The subsequent emergence of the fully elaborated generalized equivalence classes A1′–B1′–C1′ and A2′–B2′–C2′ was tracked with the sequential presentation of A′–C′, C′–A′, C′–B′, and B′–C′ probes. Finally, the robustness of these classes was evaluated with test blocks that contained A′–C′, C′–A′, C′–B′, B′–C′, A′–B′ and B′–A′ probes all of which were presented in a randomized order.

Method

Participants, Apparatus, and Stimuli

The participants were six college students with circumstances like those described in Experiment 1. The same apparatus was used in Experiment 3 as in the prior experiments. Experiment 3 used stimuli from Domains W, X, Y, Z, A, B, and C.

Procedure

Session 1 replicated Phases 1 and 2 of Experiment 1 to familiarize participants with keyboard requirements and to induce a generalized categorization repertoire. Once completed, the measurement procedures described in Phase 3 of Experiment 1 were used to determine the widths and boundaries of the six perceptual classes A1′, A2′, B1′, B2′, C1′, and C2′. Session 2 of Experiment 3 involved the establishment of the two linked perceptual classses, A1′–B1′ and A2′–B2′. This was accomplished using the procedures described in Phases 4 and 5 of Experiment 1. Phase 4 involved the training of the Aa–Ba and Ab–Bb conditional discriminations and testing for the emergent symmetrical relations, Ba–Aa and Bb–Ab. Phase 5 involved the presentation of the A′–B′ and B′–A′ probes to track the emergence of the linked perceptual classes. Their emergence was confirmed if at least 17 of the 18 probes produced mastery levels of responding. If that occurred Session 2 was terminated. On the other hand, if performance on fewer than 17 of the probe trials met the mastery criterion, the failed probes were presented for a second time. The performances on the probe trials in the first and second tests were combined, and, if at least 17 of them met the mastery criterion, the aggregated performance was taken as evidence of the delayed emergence of the linked perceptual classes. This ended Session 2.

Session 3 was conducted from 1 to 8 days after Session 2 (a 1-day delay for participants 17 and 20, a 2-day delay for participant 21, a 7-day delay for participants 16 and 18, and an 8-day delay for participant 19). Session 3 included four phases. Phase 6 tested for the Aa→Ba and Ab→Bb conditional discriminations. During Phase 7 new conditional discriminations were established between some members of the B′ and C′ classes. Phase 8 assessed the expansion of the linked perceptual classes to fully elaborated generalized equivalence classes. Finally, Phase 9 measured the robustness of the fully elaborated generalized equivalence classes with the presentation of all emergent relations probes in the same test block.

Phase 6. Test of the linked perceptual classes. Phase 6 of Experiment 3 was used to evaluate the intactness of the previously trained relations A1a→B1a, A1b→B1b, A2a→B2a, and A2b→B2b, as well as their symmetrical counterparts, B1a→A1a, B1b→A1b, B2a→A2a, and B2b→A2b. These tests were conducted with noninformative feedback. The procedures used in Phase 6 were the same as those used for Group 2 in Experiment 2 at the outset of Session 3. The trials used in Phase 6 (FEGEC) are listed in Table 1.

Phase 7. Training and testing of conditional discriminations involving the B′ and C′ classes. Phase 7 of Experiment 3 was similar to Phase 6 of Experiment 1 and was used to establish conditional discriminations involving the Ba and Ca stimuli in a pair of B′ and C′ classes (B1a→C1a, B2a→C2a,), and another set of

Table 6

Cross-class probes used to evaluate the emergence of fully elaborated generalized equivalence classes in Experiment 3.

Test Block	Row #	Probes in Block	Class 1 probes				Class 2 probes			
			Sa	Co+	Co−	Co−	Sa	Co+	Co−	Co−
Aamb–Ca	1	Aa—>Ca	$A1^a$	$C1^a$	$C2^a$	NC	$A2^a$	$C2^a$	$C1^a$	NC
	2	Am–>Ca	$A1^m$	$C1^a$	$C2^a$	NC	$A2^m$	$C2^a$	$C1^a$	NC
	3	Ab—>Ca	$A1^b$	$C1^a$	$C2^a$	NC	$A2^b$	$C2^a$	$C1^a$	NC
Aamb–Cm	4	Aa—>Cm	$A1^a$	$C1^m$	$C2^m$	NC	$A2^a$	$C2^m$	$C1^m$	NC
	5	Am–>Cm	$A1^m$	$C1^m$	$C2^m$	NC	$A2^m$	$C2^m$	$C1^m$	NC
	6	Ab—>Cm	$A1^b$	$C1^m$	$C2^m$	NC	$A2^b$	$C2^m$	$C1^m$	NC
Aamb–Cb	7	Aa—>Cb	$A1^a$	$C1^b$	$C2^b$	NC	$A2^a$	$C2^b$	$C1^b$	NC
	8	Am–>Cb	$A1^m$	$C1^b$	$C2^b$	NC	$A2^m$	$C2^b$	$C1^b$	NC
	9	Ab—>Cb	$A1^b$	$C1^b$	$C2^b$	NC	$A2^b$	$C2^b$	$C1^b$	NC
Camb–Aa	10	Ca—>Aa	$C1^a$	$A1^a$	$A2^a$	NC	$C2^a$	$A2^a$	$A1^a$	NC
	11	Cm–>Aa	$C1^m$	$A1^a$	$A2^a$	NC	$C2^m$	$A2^a$	$A1^a$	NC
	12	Cb—>Aa	$C1^b$	$A1^a$	$A2^a$	NC	$C2^b$	$A2^a$	$A1^a$	NC
Camb–Am	13	Ca->Am	$C1^a$	$A1^m$	$A2^m$	NC	$C2^a$	$A2^m$	$A1^m$	NC
	14	Cm->Am	$C1^m$	$A1^m$	$A2^m$	NC	$C2^m$	$A2^m$	$A1^m$	NC
	15	Cb–>Am	$C1^b$	$A1^m$	$A2^m$	NC	$C2^b$	$A2^m$	$A1^m$	NC
Camb–Ab	16	Ca–>Ab	$C1^a$	$A1^b$	$A2^b$	NC	$C2^a$	$A2^b$	$A1^b$	NC
	17	Cm->Ab	$C1^m$	$A1^b$	$A2^b$	NC	$C2^m$	$A2^b$	$A1^b$	NC
	18	Cb–>Ab	$C1^b$	$A1^b$	$A2^b$	NC	$C2^b$	$A2^b$	$A1^b$	NC
Bamb–Ca	1	Ba—>Ca	$B1^a$	$C1^a$	$C2^a$	NC	$B2^a$	$C2^a$	$C1^a$	NC
	2	Bm–>Ca	$B1^m$	$C1^a$	$C2^a$	NC	$B2^m$	$C2^a$	$C1^a$	NC
	3	Bb—>Ca	$B1^b$	$C1^a$	$C2^a$	NC	$B2^b$	$C2^a$	$C1^a$	NC
Bamb–Cm	4	Ba->Cm	$B1^a$	$C1^m$	$C2^m$	NC	$B2^a$	$C2^m$	$C1^m$	NC
	5	Bm->Cm	$B1^m$	$C1^m$	$C2^m$	NC	$B2^m$	$C2^m$	$C1^m$	NC
	6	Bb–>Cm	$B1^b$	$C1^m$	$C2^m$	NC	$B2^b$	$C2^m$	$C1^m$	NC
Bamb–Cb	7	Ba->Cb	$B1^a$	$C1^b$	$C2^b$	NC	$B2^a$	$C2^b$	$C1^b$	NC
	8	Bm->Cb	$B1^m$	$C1^b$	$C2^b$	NC	$B2^m$	$C2^b$	$C1^b$	NC
	9	Bb–>Cb	$B1^b$	$C1^b$	$C2^b$	NC	$B2^b$	$C2^b$	$C1^b$	NC
Camb–Ba	10	Ca—>Ba	$C1^a$	$B1^a$	$B2^a$	NC	$C2^a$	$B2^a$	$B1^a$	NC
	11	Cm–>Ba	$C1^m$	$B1^a$	$B2^a$	NC	$C2^m$	$B2^a$	$B1^a$	NC
	12	Cb—>Ba	$C1^b$	$B1^a$	$B2^a$	NC	$C2^b$	$B2^a$	$B1^a$	NC
Camb–Bm	13	Ca->Bm	$C1^a$	$B1^m$	$B2^m$	NC	$C2^a$	$B2^m$	$B1^m$	NC
	14	Cm->Bm	$C1^m$	$B1^m$	$B2^m$	NC	$C2^m$	$B2^m$	$B1^m$	NC
	15	Cb–>Bm	$C1^b$	$B1^m$	$B2^m$	NC	$C2^b$	$B2^m$	$B1^m$	NC
Camb–Bb	16	Ca->Bb	$C1^a$	$B1^b$	$B2^b$	NC	$C2^a$	$B2^b$	$B1^b$	NC
	17	Cm->Bb	$C1^m$	$B1^b$	$B2^b$	NC	$C2^m$	$B2^b$	$B1^b$	NC
	18	Cb–>Bb	$C1^b$	$B1^b$	$B2^b$	NC	$C2^b$	$B2^b$	$B1^b$	NC

Note. Each row lists the stimuli in two cross-class probes. The A′–B′ and B′–A′ probes were presented first, as shown in Table 2, but do not appear here. The stimuli are represented symbolically. Both probes in each row shared the same set of comparisons, but the positive comparison (Co+) was different for each class. Superscripts a, b, and m = anchor, midpoint, and boundary stimuli, respectively. NC = the neither comparison. Rows 1–9 (top) list the probes used to assess generalization of transitivity. Rows 10–18 (top) list the probes used to assess generalization of equivalence. Rows 1–18 (bottom) list the probes used to evaluate the emergence of the B′=C′ linked perceptual classes.

conditional discriminations involving the Bb and Cb stimuli in the same pair of classes (B1b→C1b, and B2b→C2b). Tests were conducted to assess the symmetrical properties of the stimuli in each relation.

Phase 8. Emergence of fully elaborated generalized equivalence classes. Phase 8 involved the presentation of probe trials to evaluate the expansion of each linked perceptual class to a fully elaborated generalized equivalence class. Each block contained 16 trials. On 8 of the trials, the Class 1 stimulus was presented as the sample, and on the other 8 trials the Class 2 stimulus was presented as the sample. All of the trial types are listed by block in Table 6. First, participants were presented with A′–B′ and B′–A′ probes, then with the A′–C′ probes, which were generalization tests of transitivity, and with C′–A′ probes, which were generalization tests of equivalence. Following these was a combination of the A′–B′ and B′–C′ probes which were generalization tests of the initial linked perceptual classes, followed by a combination of the B′–A′ and C′–B′ probes, which

Table 7

Boundary stimuli of perceptual classes A1′, A2′, B1′, B2′, C1′ and C2′ with variant-to-base (VB) and base-to-variant (BV) tests for participants in Experiment 3.

	Perceptual Classes											
	A1′		A2′		B1′		B2′		C1′		C2′	
Participant	VB	BV	VB	BV	VB	BV	VB	BV	VB	BV	VB	BV
16	15	18	40	43	170	170	310	310	12	09	28	28
17	18	18	34	34	130	170	310	280	15	15	37	34
18	15	15	40	40	170	130	310	340	09	12	34	34
19	15	15	34	34	130	130	310	310	15	15	34	31
20	18	21	37	34	170	210	310	310	15	15	25	21
21	18	18	37	37	170	170	310	280	15	09	40	25
Mean	**17**	**18**	**37**	**37**	**157**	**163**	**310**	**305**	**14**	**13**	**33**	**29**
Min-Max[1]	**00**	**00**	**50**	**50**	**000**	**000**	**500**	**500**	**00**	**00**	**50**	**50**

[1] Minimum and maximum values of the respective endpoint stimuli on each domain.

were generalization tests of the symmetrical relations. Finally, a second presentation of the A′–C′ probes and a second presentation of the C′–A′ probes occurred.

Phase 9. Retention of fully elaborated generalized equivalence classes. In the last phase of Experiment 3, participants were presented with four test blocks, each of which contained one trial of each type of probe used to document the fully elaborated generalized equivalence classes. The probes included in Phase 9 are listed in Table 6. Each probe type was used on four trials. For example, with the Ab–Cm probe, the A1b and A2b stimuli were each used as the sample on two trials, along with the B1m and B2m stimuli as the comparisons. When the A1b stimulus was the sample, on one trial the B1m comparison appeared on the left, and on the other trial it appeared on the right. The same change of location occurred for the two comparisons when A2b was the sample. Class membership of the sample stimuli was balanced and randomized across the four test blocks.

Results

Boundary Values and Widths of the A′, B′, and C′ Classes

Table 7 lists the boundary values of the A′, B′, and C′ classes that were measured in Phase 3 of Experiment 3. For Domain A, which had endpoint values of 0 and 50 units, the boundary stimuli of the A1′ and A2′ classes averaged 18 and 37 units, respectively, and thus were separated by an average of 19 units. The average widths for the A1′ and A2′ classes were 18 and 13 units, respectively. For Domain B, which had endpoint values of 0 and 500 units, the boundary stimuli of the B1′ and B2′ classes averaged 160 and 308 units, respectively, and were separated by an average of 148 units. The average widths for the B1′ and B2′ classes were 160 and 192 units, respectively. For Domain C, which had endpoint values of 0 and 50 units, the boundary stimuli of the C1′ and C2′ classes averaged 14 and 31 units, respectively, and were separated by an average of 17 units. The average widths for the C1′ and C2′ classes were 14 and 19 units, respectively.

Discriminability of Stimuli in Perceptual Classes

In the A′ classes, mean response speeds were fastest (0.94 responses/s) for the anchor stimuli, slower (0.77 responses/s) for the midpoint stimuli, and slowest (0.50 responses/s) for the boundary stimuli. In the B′ classes, mean response speeds were fastest (.61 responses/s) for the anchor stimuli, slower (0.40 responses/s) for the midpoint stimuli, and slowest (0.24 responses/s) for the boundary stimuli. Similarly, in the C′ classes, mean response speeds were fastest (0.65 responses/s) for the anchor stimuli, slower (0.56 responses/s) for the midpoint stimuli, and slowest (0.37 responses/s) for the boundary stimuli. In general, response speeds decreased systematically as the value of the variant changed from the anchor, to the midpoint, to the boundary stimulus of a class. With the one exception of the anchor and midpoint of the C′ class, pairwise post hoc comparisons showed that the response speeds within a class were significantly different from each other.

Evaluation of Conditional Discriminations for All Classes

The training of the conditional discriminations for linked perceptual classes and fully elaborated generalized equivalence classes was separated by the tests used to evaluate the emergence of the linked perceptual classes. The data regarding the acquisition of the initial conditional discriminations for both types of classes, however, will be presented together and precede the presentation of the data used to demonstrate the emergence of linked perceptual classes and fully elaborated generalized equivalence classes.

Retention of Aa→Ba and Ab→Bb in Session 3

At the beginning of Session 3 all of the participants were presented with previously established *Aa→Ba and Ab→Bb* conditional discriminations in the absence of informative feedback. For all participants, all trials produced criterial levels of responding, which demonstrated the maintenance of the previously trained conditional discriminations over the course of 1–8 day delays.

Ba→Ca and Bb→Cb Training, Retention, and Symmetry in Session 3

A minimum of 3 blocks was scheduled for the establishment of the Ba–Ca and Bb–Cb conditional discriminations. On these blocks, feedback was provided on all trials. The average number of blocks required to achieve the criterion for acquisition was 5.0 for 5 of the 6 participants. This number was close to the required minimum; therefore, acquisition was rapid for these participants. The 6th participant (Participant 21) required 16 blocks to acquire the Ba–Ca and Bb–Cb conditional discriminations. Coincidentally, this participant was the only participant who did not demonstrate the emergence of fully elaborated generalized equivalence classes as shown later in this section. For all participants criterial-level discriminative performances were maintained during feedback reduction. Finally, 100% accuracy occurred on the first presentation of the symmetry probes, Ca–Ba and Cb–Bb.

Emergence of Fully Elaborated Generalized Equivalence Class

A fully elaborated generalized equivalence class emerged when most of the members of an A′, B′, and C′ classes produce the mutual selection of each other. This meant that at least 17 of the 18 cross-class probes in the A′–B′ and B′–A′ tests produced at least 88% class-consistent responding, at least 17 of the 18 cross-class probes in the B′–C′ and C′–B′ tests produced at least 88% class-consistent responding, and at least 17 of the 18 cross-class probes in the A′–C′ and C′–A′ tests produced at least 88% class-consistent responding.

The emergence of linked perceptual classes, A′=B′, B′=C′, and A′=C′, and their expansion to fully elaborated generalized equivalence classes, A′=B′=C′, was evaluated using the data presented in Figures 7–12. Each figure represents one of the participants in Experiment 3.

The data in Figure 7 are for Participant 16. The panels in the first two rows in Figure 7 contain test results for the emergence of linked perceptual classes A1′=B1′ and A2′=B2′. All of the A′–B′ and B′–A′ probes produced the criterial levels of class-consistent comparison selection.

The data in the subsequent rows were obtained after the training of the Ba→Ca and Bb→Cb relations (indicated by the heavy dashed line). Rows 3 and 4 show the results of generalization tests of transitivity, A′–C′, and generalization tests of equivalence, C′–A′. All of these probes occasioned criterial levels of selection of the class-consistent comparisons, which demonstrated the emergence of relations among the variants of A′and C′ classes without any direct training. Although the results of the A′–C′ and C′–A′ tests suggest the emergence of fully- elaborated generalized equivalence classes, they were not definitive because relations between the variants in the B′ and C′ classes were not yet confirmed.

The data in rows 5 and 6 illustrate the performances produced by the generalization tests of the baseline relations, A′–B′ and B′–C′, and their corresponding generalization tests of symmetry, B′–A′ and C′–B′. In all cases, performance met the criterion for class-consistent selection. The performances evoked by the A′–B′ and B′–A′ probes demonstrated the retention of the A′=B′ linked perceptual classes. The performances produced by the B′–C′ and C′–B′ probes demonstrated the emergence of the B′=C′ linked perceptual classes. The results from the probes depicted in rows 1 through 6 confirmed the emergence

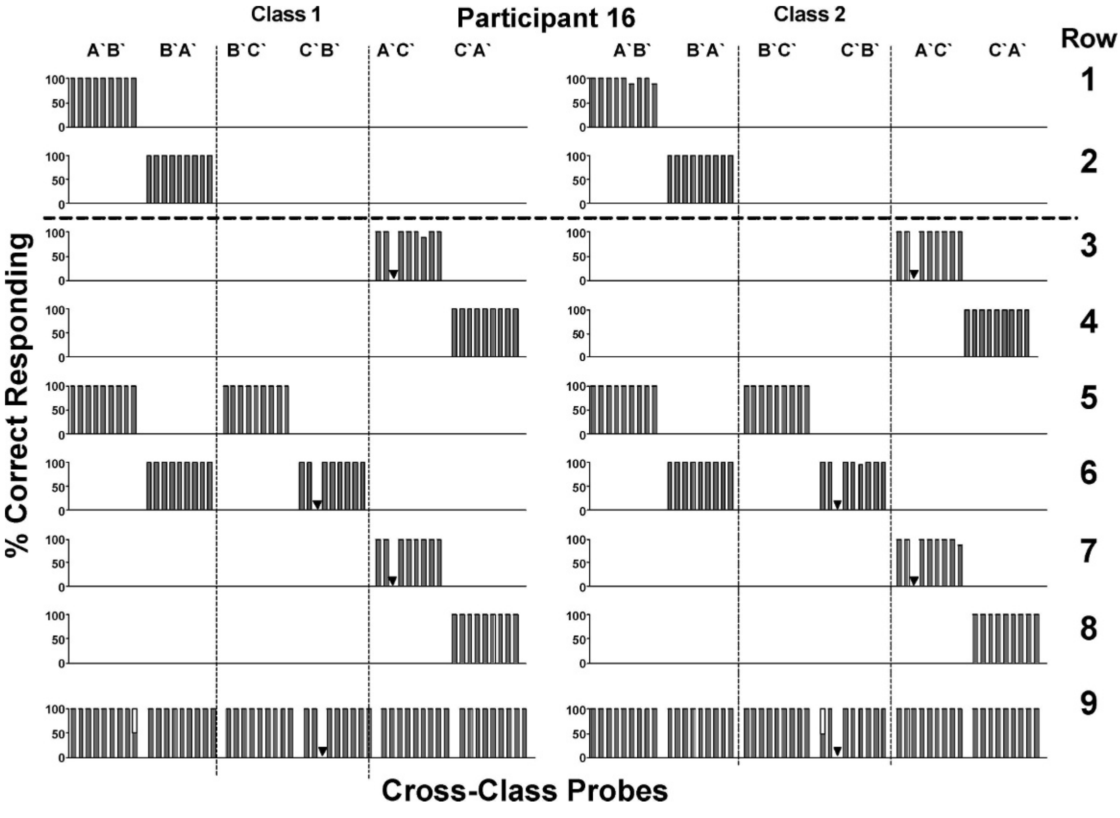

Fig. 7. Results of probe testing used to evaluate the emergence of linked peceptual classes and fully elaborated equivalence classes for Participant 16 in Experiment 3. The panels on the left and right are for classes 1 and 2, respectively. Read from left to right, the column headings represent the types of cross-class probes used in Experiment 3. The bars shown in each row are for different types of cross-class probes. Rows 1 and 2 display the results of the A′–B′ and B′–A′ tests, which tracked the emergence of the initial linked perceptual classes. The thick dashed horizontal line between rows 2 and 3 designates the break between Sessions 2 and 3 and also indicates when B′–C′ training began. The remaining rows display results from Session 3. Rows 3 and 4 display the data from the generalization tests of transitivity, A′–C′, and equivalence, C′–A′, respectively. Rows 5 and 6 display the results from the generalization test of the baseline conditional discriminations, A′–B′ and B′–C′, and the corresponding tests for the generalization of symmetry B′–A′ and C′–B′, respectively. Rows 7 and 8 show results from retesting for the generalization of transitivity, A′–C′, and equivalence, C′–A′, respectively. Row 9 displays the data from the condition in which all probes were included in the same test blocks. The rows are numbered sequentially and represent the order of presentation of the relational tests. For example, the C′–A′ probe test was presented fourth in the sequence. All of the bars in a row indicate specific tests that were presented in a given block of test trials. With the exception of the last row, all of the probes in a row were presented in the left-to-right order indicated. All probes in the bottom row were presented in a randomized sequence in the same test block. The abscissa lists the specific probes used in each test. Each type of cross-class probe (e.g. A′–B′) is represented by a cluster of nine bars. Moving from left to right in each cluster, the bars represent performances evoked by the aa, ma, ba, am, mm, bm, ba, bm, and bb probes, respectively. The left and right letters in each letter pair represent the sample and comparison used in each probe, with a, m and b representing the anchor (a), midpoint (m) and boundary (b) values, respectively. For example, the third bar in the B′–C′ column designated as ba refers to the Bb–Ca probe. The height of each bar indicates the percentage of trials of a given probe that produced class-consistent responding. Gray bars indicate the percentage of trials that produced selection of the class-consistent comparison. White bars indicate the percentage of trials that produced selection of a comparison that was from a different class. Black bars indicate the percentage of trials that produced selection of the neither comparison. The dots above bars indicate the relations that were directly trained. A black triangle indicates that the probe was not presented due to a programming error.

of fully elaborated generalized equivalence classes, A′=B′=C′. To summarize, the data in rows 3–6 demonstrate: (a) the emergence of relations among the variants in the A′ and C′ classes, and the maintenance of previously established A′=B′ linked perceptual classes; (b) the initial emergence of the B′=C′ linked perceptual classes; and (c) the emergence of

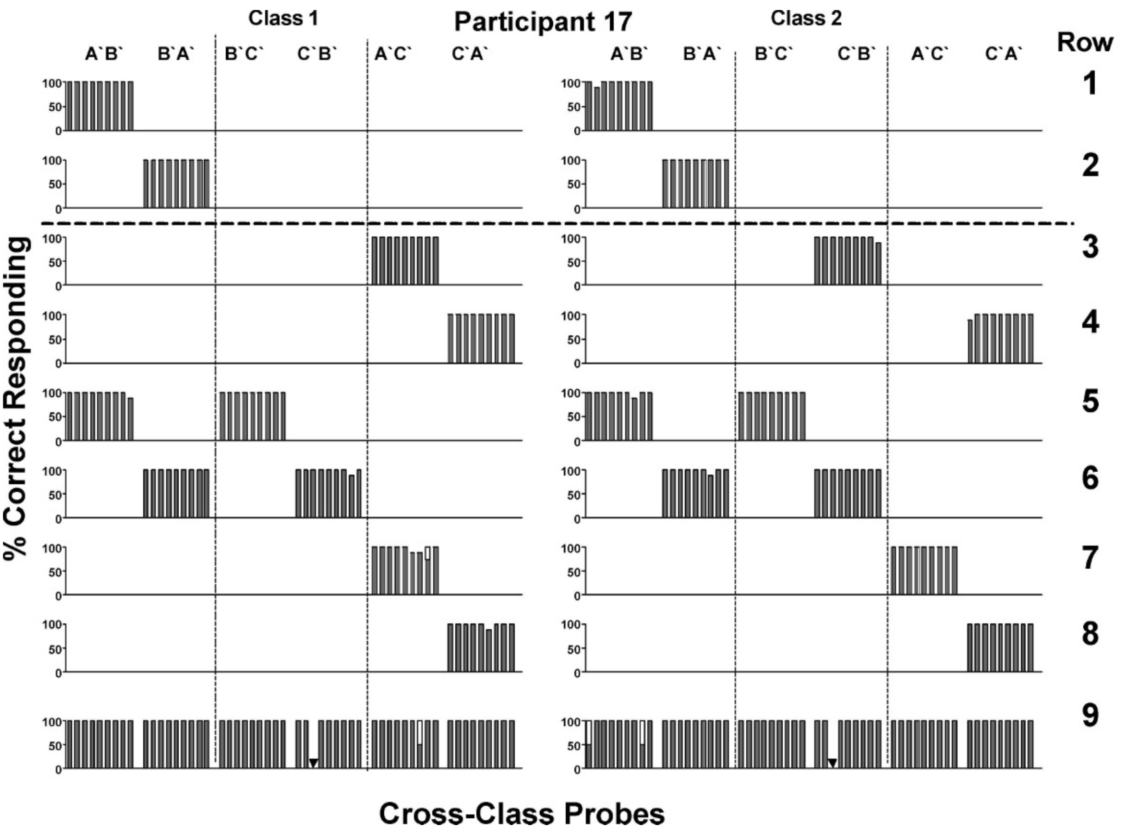

Fig. 8. Probe data for Participant 17 in Experiment 3. The format is the same as that used for Figure 7.

the A′=B′=C′ fully elaborated generalized equivalence classes.

The data displayed in rows 7 and 8 are those from the repetition of the generalization tests of transitivity and equivalence. In all cases, the probes continued to produce criterial levels of the selection of the class-consistent comparison which demonstrated the retention of the A′–C′ and C′–A′ relations. Finally, the data in row 9 illustrate the results when all of the probes were presented in the same test block. Although 54 probes should have been presented, a programming error resulted in the presentation of only 53 probes in each fully elaborated generalized equivalence class. For both classes, 52 of the 53 occasioned criterial levels of responding. These results demonstrate the robustness of the relations among the stimuli in each of the A′=B′=C′ fully elaborated generalized equivalence classes despite the randomized presentation of all but one of the possible emergent relations probes in the same test block.

The data for the remaining participants in Experiment 3 are presented in a format similar, if not identical, to that used in Figure 7. The results obtained for Participant 17 are presented in Figure 8. This participant's were essentially identical to those obtained from Participant 16.

The data for Participant 18 are presented in Figure 9. In general, the data were similar to those described for Participants 16 and 17, with the following exception. For each class, the criterion for the linked perceptual classes was not achieved in initial A′–B′ test (see row 1). The failed probes produced criterion levels of responding with the retest, as seen in row 2. Thereafter, the aggregate performances produced by the A′–B′ probes presented in rows 1 and 2 and the B′–A′ probes (in row 3) documented the delayed emergence of the A′=B′ linked perceptual classes. The performances of the other probes presented in the remaining rows documented their ready expansion to

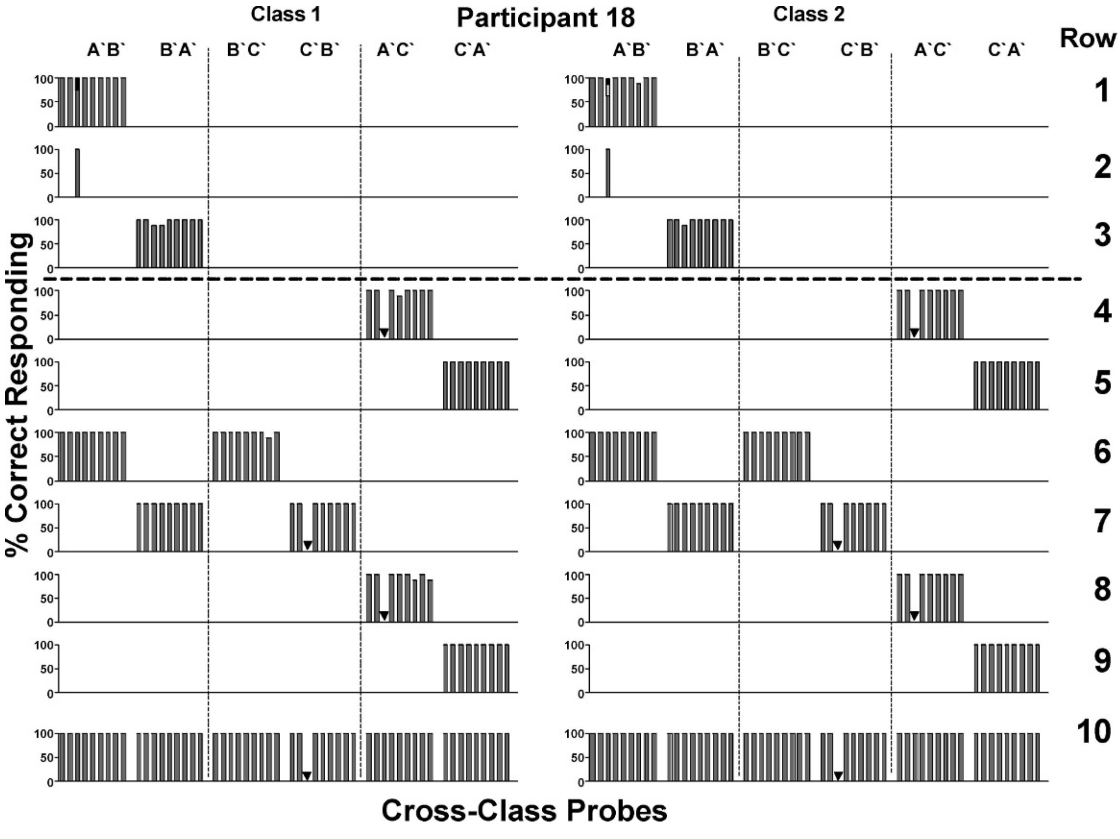

Fig. 9. Probe data for Participant 18 in Experiment 3. The format is similar to that used for Figure 7 with one exception. A new second row is interposed to show the results of retesting with the probes that failed to produce criterial performance during the initial A′–B′ tests.

A′=B′=C′ fully elaborated generalized equivalence classes

The data for Participant 19 are presented in Figure 10. With the exception of two failed A′–B′ probes, the results were essentially identical to those obtained for Participant 18 in Figure 9.

The data for Participant 20 are presented in Figure 11. This participant passed the A′–B′ tests (as seen in row 1) but failed three of the nine symmetrical B1′–A1′ probes (as seen in row 2). Retesting of the failed probes (third row) produced the criterial level of responding that demonstrated the delayed and immediate emergence of the A1′=B1′ and A2′=B2′ linked perceptual classes, respectively. The remaining probes produced class-consistent selections that demonstrated the immediate emergence of the B′=C′ linked perceptual classes, the A′=B′=C′ fully elaborated generalized equivalence classes, and their retention.

The data for Participant 21 are presented in Figure 12. The initial performances produced by the A′–B′ and B′–A′ probes showed the formation of the linked perceptual classes. After B′–C′ training, however, the A′–C′ and C′–A′ probes in both classes did not evoke criterial levels of responding. Thereafter, all of the A′–B′ and B′–A′ probes as well as the B′–C′ and C′–B′ probes evoked those levels (see rows 5 and 6). These results showed the maintenance of the A′=B′ linked perceptual classes and the immediate emergence of the B′=C′ linked perceptual classes. Reexposure to the A′–C′ and C′–A probes (see rows 7 and 8) almost always resulted in the the selection of Class 1 comparisons in the presence of Class 2 samples and vice versa. Thus, fully elaborated generalized equivalence classes did not emerge for this participant.

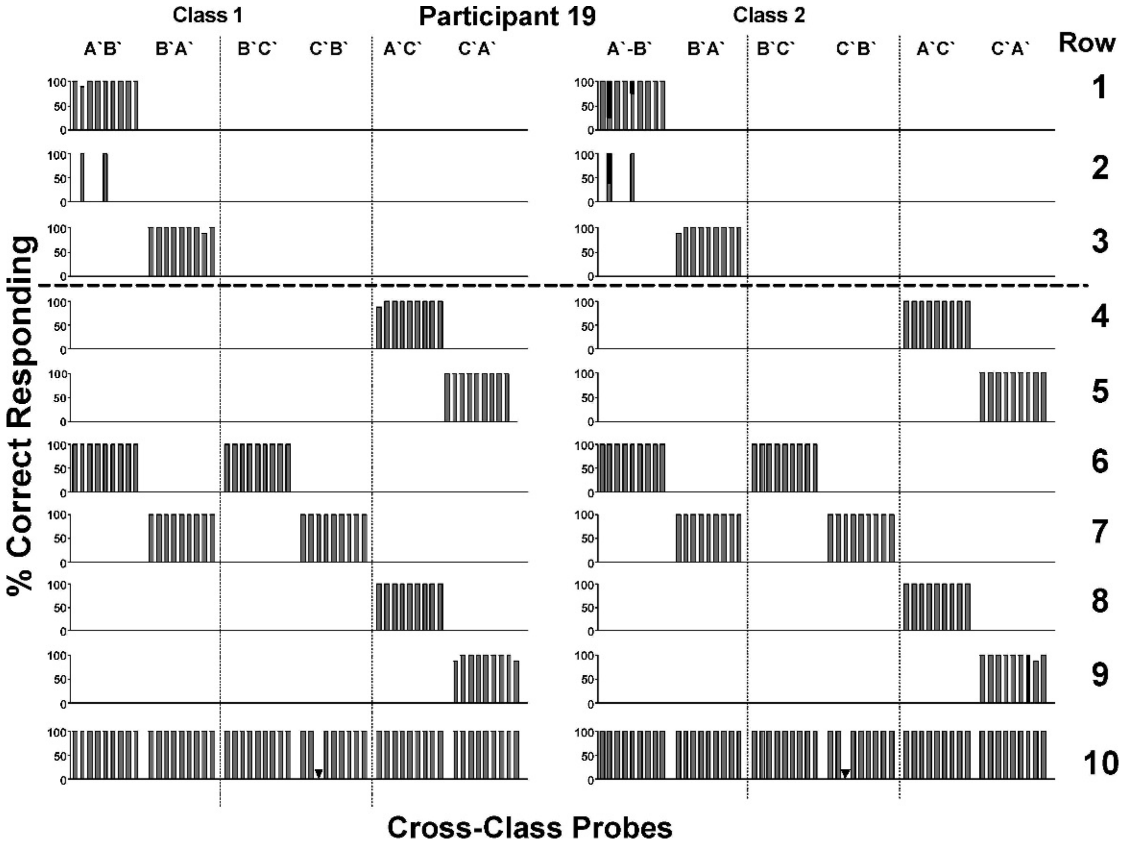

Fig. 10. Probe data for for Participant 19 in Experiment 3. The format is same as that used in Figure 9.

Discussion

All 6 participants in Experiment 3 formed linked perceptual classes A1′–B1′ and A2′–B2′. The classes emerged rapidly for 4 participants but on a delayed basis for the 2 remaining participants. For 5 of the 6 participants, after the establishment of Ba–Ca and Bb–Cb conditional discriminations, all of the probes produced selection of the class-consistent comparison at the criterial level. These performances demonstrated the emergence of the B′=C′ linked perceptual classes after training of relations between some of the stimli in B′ and C′ classes. The performances produced by the A′–C′ and C′–A′ probes demonstrated the emergence of the derived relations among the stimuli in the A′ and C′ classes. Finally, the entire set of probe data demonstrated the expansion of the linked perceptual classes to fully elaborated generalized equivalence classes and their maintenance thereafter.

For one participant, however, fully elaborated generalized equivalence classes did not emerge. This participant responded in a class-indicative manner to the A′–B′ and B′–A′ probes as well as the B′–C′ and C′–B′ probes. These performances demonstrated the emergence of the A′=B′ and B′=C′ classes. In contrast, the A′–C′ and C′–A′ probes did not produce class-consistent responding. This outcome could not reflect the absence of relations between A′ and B′ stimuli because the presence of the A′=B′ classes were documented before and after the A′–C′ and C′–A′ tests., It might be argued that the failed performances during the A′–C′ and C′–A′ tests were due to the absence of a relations between the A′ and C′ stimuli. That is also not plausible because the emergence of the B′=C′ classes was demonstrated after the initial presentation of the A′–C′ and C′–A′ tests (rows 3 and 4) and before the second presentation of the latter tests (rows 7 and 8). Rather, the

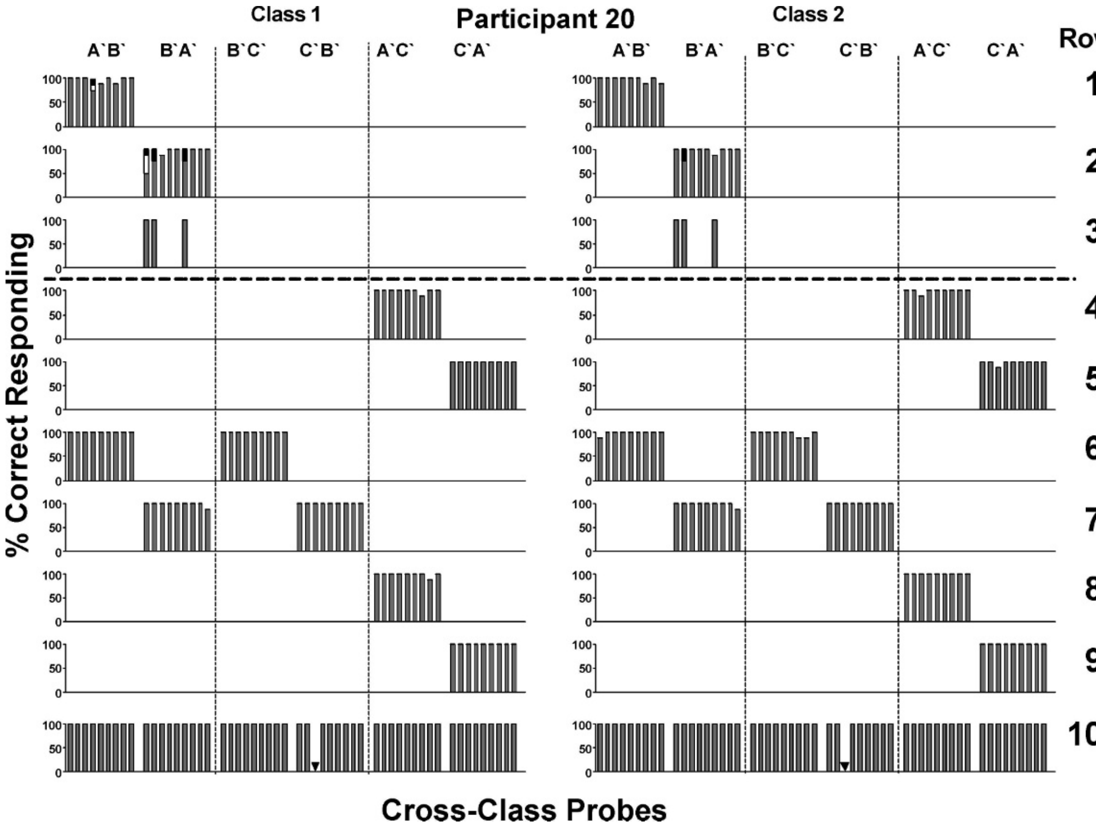

Fig. 11. Probe data for Participant 20 in Experiment 3. The format is similar to that used for Figure 9 with one exception. A new third row is interposed to show the results of retesting the probes that failed to produce criterial performance during the initial B′–A′ tests.

A′=B′=C′ classes were not formed because transitivity did not emerge between the A′ and C′ stimuli that were members of the A′=B′ and B′=C′ classes. The emergence of fully elaborated generalized equivalence classes might have been enhanced by training a transitivity repertoire that generalized to many new stimulus sets (i.e., a generalized transitivity repertoire) prior to the establishment of generalized equivalence classes (Fields et al., 2000). Future research may address the viability of this notion.

The robustness of a fully elaborated generalized equivalence class can be evaluated by measuring the resistance to disruption of the classes by the addition of other variables. The emergence of fully elaborated generalized equivalence classes was demonstrated in the current experiment by using sequentially presented emergent relations probes. The disruptor was the presentation of all of the probes in single test blocks, which occurred in Phase 9. For 5 of the 6 participants, however, all the probes continued to evoke class-consistent responding, thereby providing evidence that fully elaborated generalized equivalence classes are robust.

GENERAL DISCUSSION

Maximizing the Formation of Linked Perceptual Classes

Maximization, as used here, means that all of the participants in an experiment form the target classes. Alternatively, optimization means that some of the participants in an expeirment form the target classes but that the percentage is less than 100% because of the constraints imposed by some of the fixed parameters of the experiment (see Fields et al., 2005, 2007). In a prior experiment (Fields et al., 2007), the formation of a linked

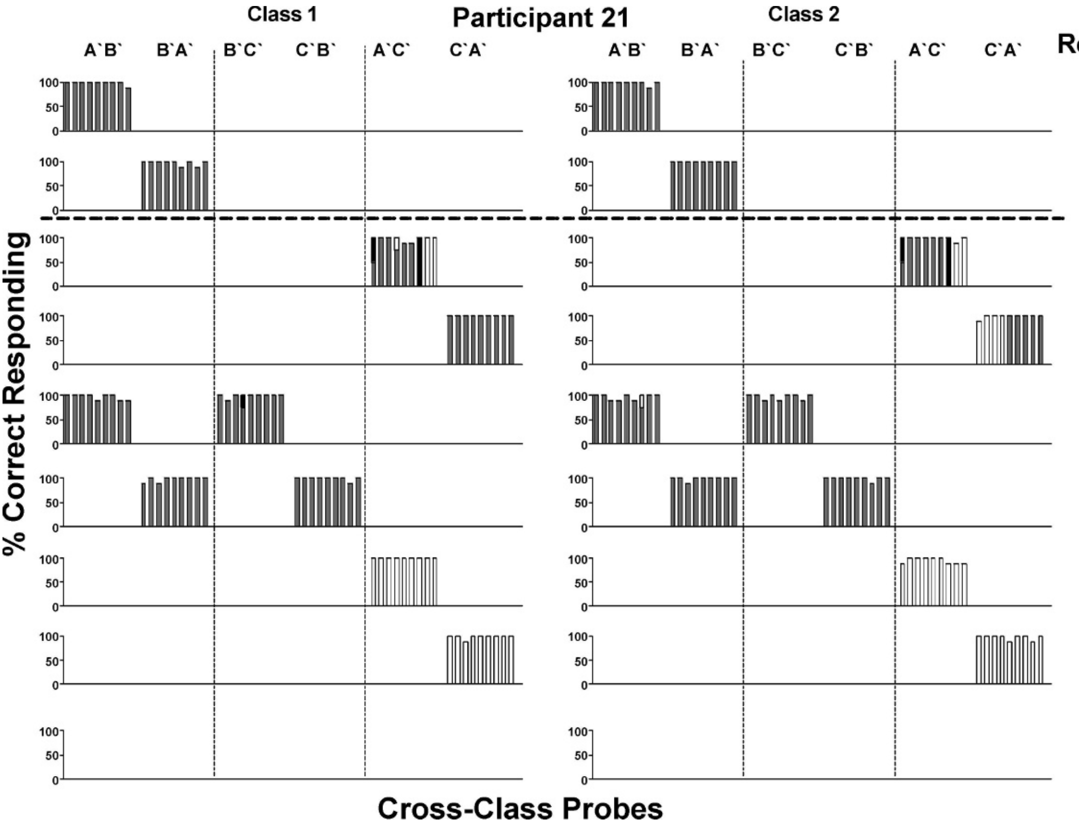

Fig. 12. Data from probe trials for Participant 21 in Experiment 3. The format is the same as that used for Figure 7. No data are included in the bottom panel because the mixed test was not conducted for this participant.

perceptual class was optimized, but not maximized, by training the two cross-class conditional discriminations, Aa–Ba and Ab–Bb. In other words, optimization resulted from the testing schedule used in that experiment. In addition, Fields et al. (2005) had shown that the emergence of linked perceptual classes was optimized, but not maximized, by use of the 18/1-PRGM test design. By implication, the formation of linked perceptual classes ought to be maximized by the use of the optimal training procedure described by Fields et al. (2005) in combination with that described by Fields et al. (2007). The results of the three experiments confirmed this prediction. Linked perceptual classes were formed by all 21 individuals who served as participants in these experiments. Specifically, the formation of linked perceptual classes was maximized by training the Aa–Ba and Ab–Bb relations and tracking the emergence of the classes using the 18/1- PRGM testing schedule.

Fully Elaborated Generalized Equivalence Classes

Fully elaborated generalized equivalence classes were established by training two conditional discriminations to link the A′ and B′ perceptual classes, and two other conditional discriminations to link the B′ and C′ classes. Class emergence was evaluated with the systematically sequenced presentation of many cross-class probes. A fully elaborated generalized equivalence class that emerges from A′–B′ and B′–C′ training has two embedded linked perceptual classes: A′=B′ and B′=C′. Prior research showed that variations in the parameters of training (Fields et al., 2007) and testing (Fields et al., 2005) influenced the likelihood of their emergence. Additional research will be needed to determine whether similar variations in training and testing also influence the formation of fully elaborated generalized equivalence classes.

Nodality Effects in Generalized Equivalence Classes

The organization of a partially or a fully elaborated generalized equivalence class can be viewed in terms of nodal structure (Fields, Adams, & Verhave, 1993b). The classes in the present experiment were established by training A′–B′ and B′–C′ relations. Thus, the A and B stimuli were not separated by any nodal stimuli, but the C′ and A′ stimuli in a class were (B′). Many experiments have shown that class-consistent responding is an inverse function of the nodal distance that separates the stimuli in an equivalence class (Bentall, Jones, & Dickins, 1998; Fields & Verhave, 1987; Fields et al., 1995; Fields et al., 1990; Kennedy, 1991; Kennedy, Itkonen, & Lindquist, 1994; Sidman, Kirk, & Willson-Morris, 1985; Spencer & Chase, 1996; Wulfert & Hayes, 1988). Three of the participants in Experiment 1 failed to show the emergence of partially elaborated generalized equivalence classes. In addition the one participant in Experiment 3 for whom fully elaborated generalized equivalence classes failed to emerge did not respond in a class-consistent manner to the A′–C′ and C′–A′ probes. For all 4 of these participants, class-consistent responding was produced by the B′–A′ and C′–B′ probes used to evaluate symmetry but not by the A′–C′ and C′–A′ probes used to evaluate transitivity and equivalence. The stimuli in the B′–A′ and C′–B′ probes were not separated by any nodal stimuli, while the stimuli in the A′–C′ and C′–A′ probes were separated by at least one nodal stimulus. Overall, then, the conditioned discrimination performance could be considered an inverse function of nodal structure.

These data suggest that the strength of relations among the stimuli in partially and fully elaborated generalized equivalence classes is influenced by nodal structure, as are the relations in equivalence classes (Fields & Moss, in press). While the present results identify the locus of failures in class formation, they do not clarify either the mechanisms or variables that are responsible for the non-emergence of the transitive and equivalence relations that can be derived from the stimuli in partially or fully elaborated generalized equivalence classes.

Generalized Equivalence Classes and Categories in Natural Settings

A fully elaborated generalized equivalence class consists of some physically similar stimuli and other physically disparate stimuli, all of which become functionally substitutable for each other. These structural and functional properties also characterize natural categories, natural kinds, and fuzzy superordinate categories (Fields & Reeve, 2000, 2001; Herrnstein, 1990; Lane et al., 1998; Lea, 1984; Lea & Harrison, 1978; Rehfeldt & Hayes, 2000; Rosch & Mervis, 1975). Granting their structural and functional similarities, the variables responsible for the establishment of fully elaborated generalized equivalence classes might also account for the establishment of the complex categories that emerge in natural settings. As mentioned in the Introduction, one example would be a category that included the sounds made by a predator species (one perceptual class), the visual appearance of members of the species (a second perceptual class), and their scents (a third perceptual class). Another such category could include the many views of an individual's face (one perceptual class), the many sounds of that individual's voice (a second perceptual class), and the name of the individual written in different fonts and by different hands (a third perceptual class).

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